RF Systems for the 3rd Generation Synchrotron Radiation Facilities

Lecture 13

Booster Synchrotron & Storage Ring

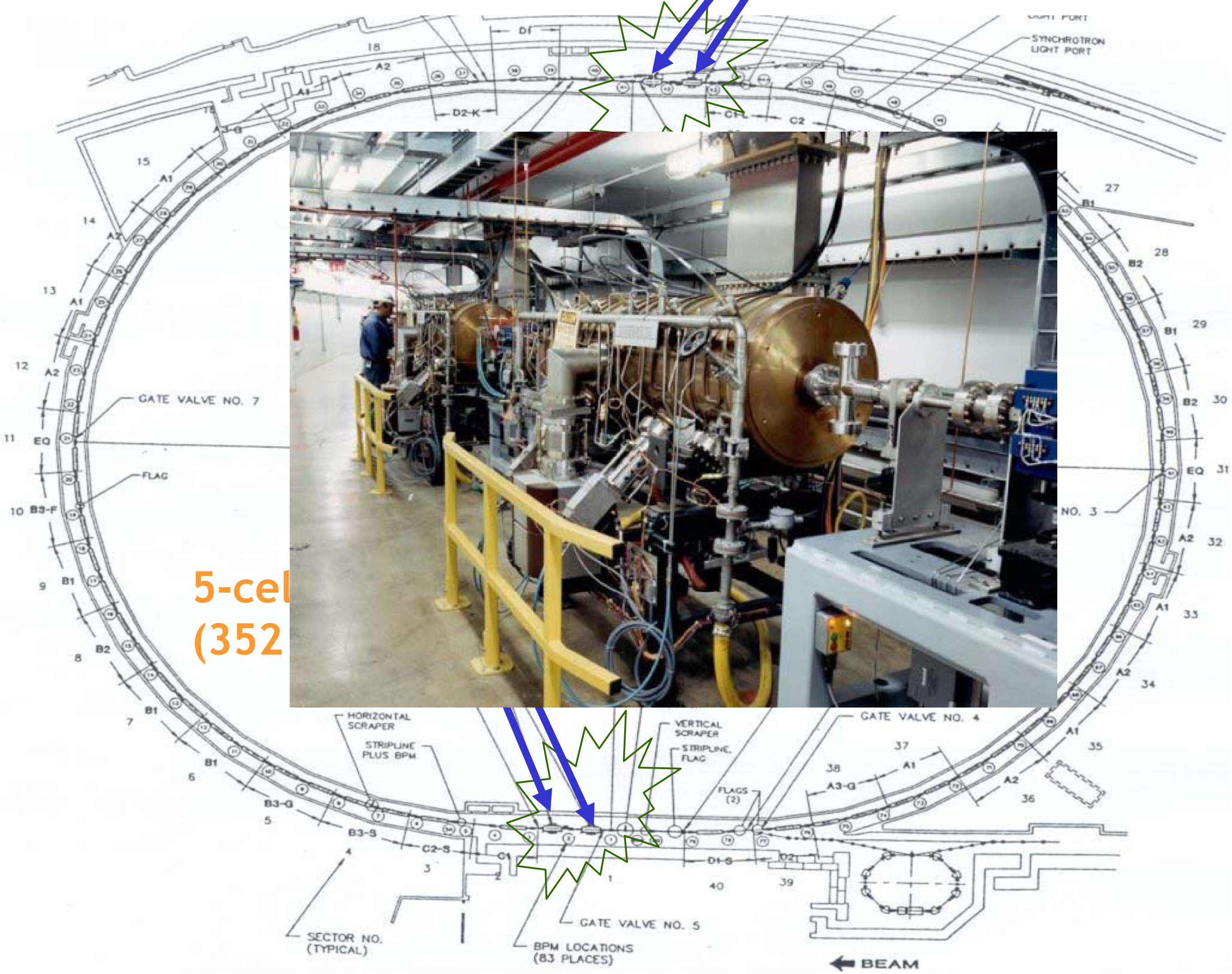
February 18, 2003

Topics:

- Booster Synchrotron
  - Injection
  - Extraction
  - Ramping
  - Beam loading
- Storage Ring
  - RF Distribution
  - HVPS
  - Klystron
  - Cavities
  - LLRF
  - Coupling/Coupler
  - HOM Effects
  - CBM Instability

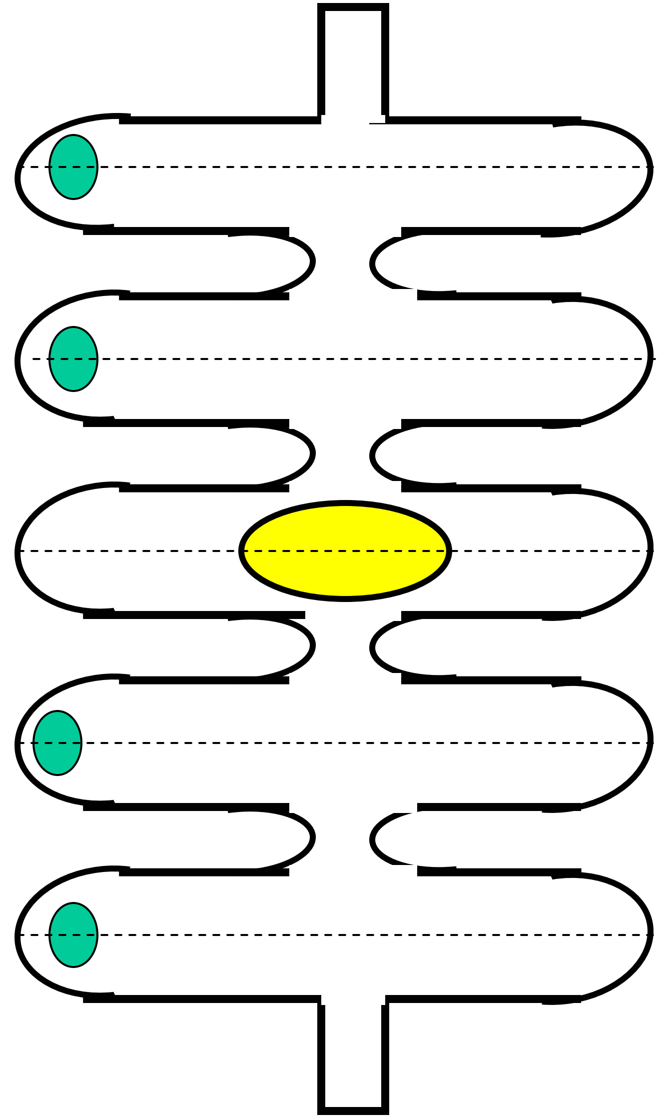
Booster Synchrotron

5-cell rf cavity
(352 MHz)



5-cel
(352

Booster Synchrotron



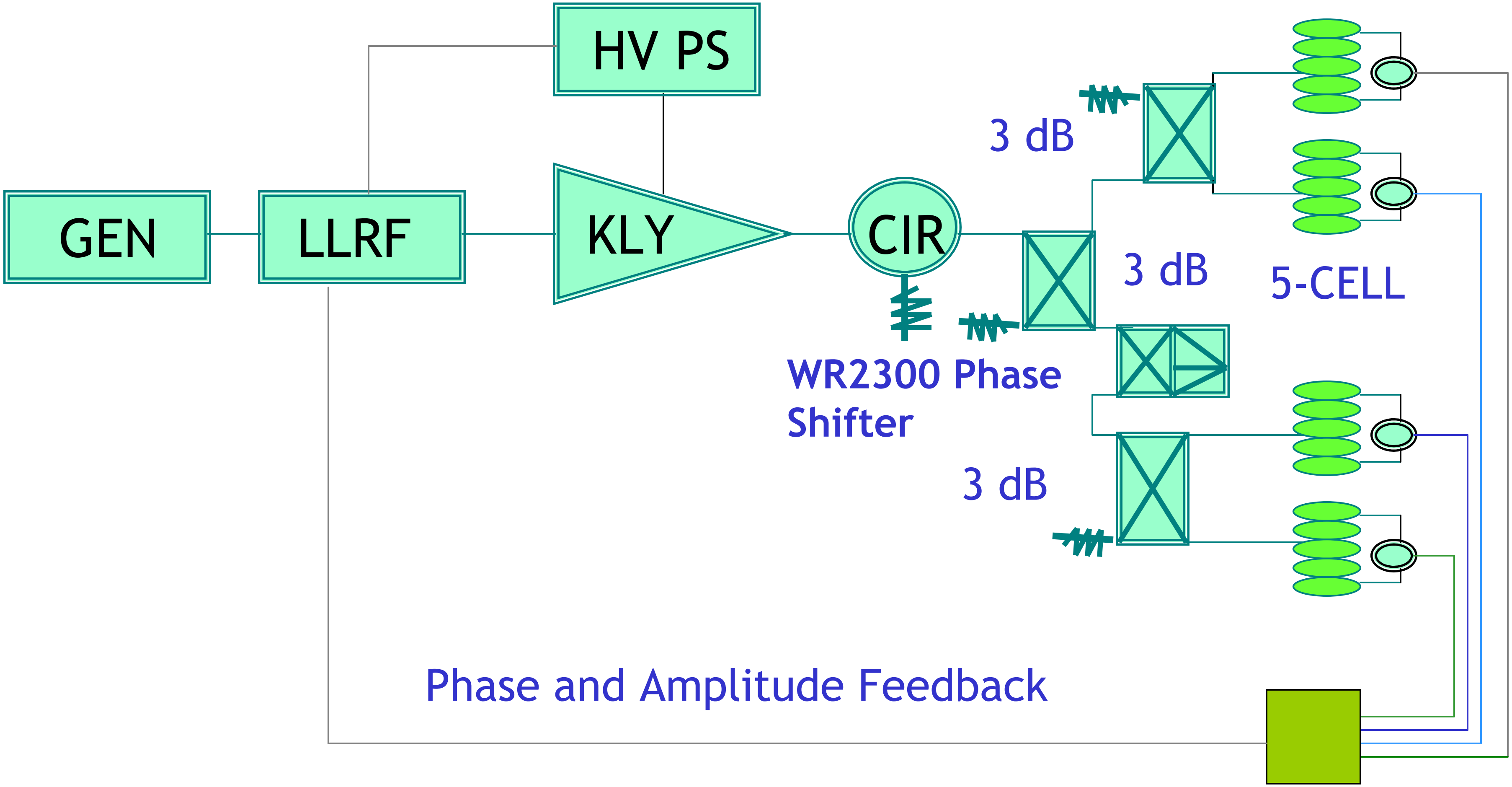
Booster 352 MHz 5 cells cavity

Booster Synchrotron

Five-Cell $\lambda/2$ 352 MHz Booster Cavity

Bore-hole diameter	10 cm
Cell length	42.6 cm
Cell radius	30.2 cm
Total length of cavity	2.32 m
Shunt impedance per cavity	55.3 MΩ
Average accelerating voltage	1.40 MV/m
Total power required	550 kW

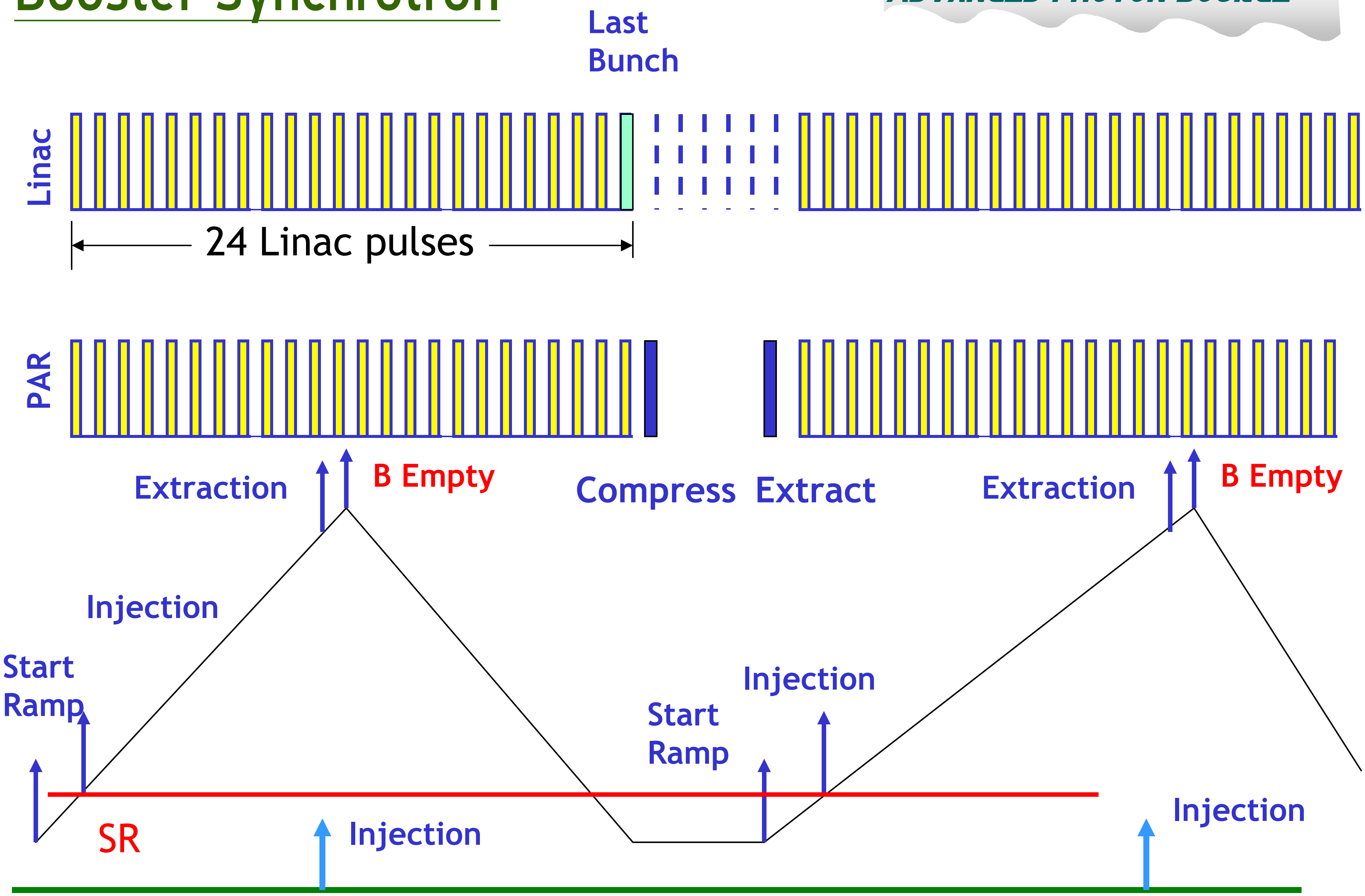
Booster Synchrotron



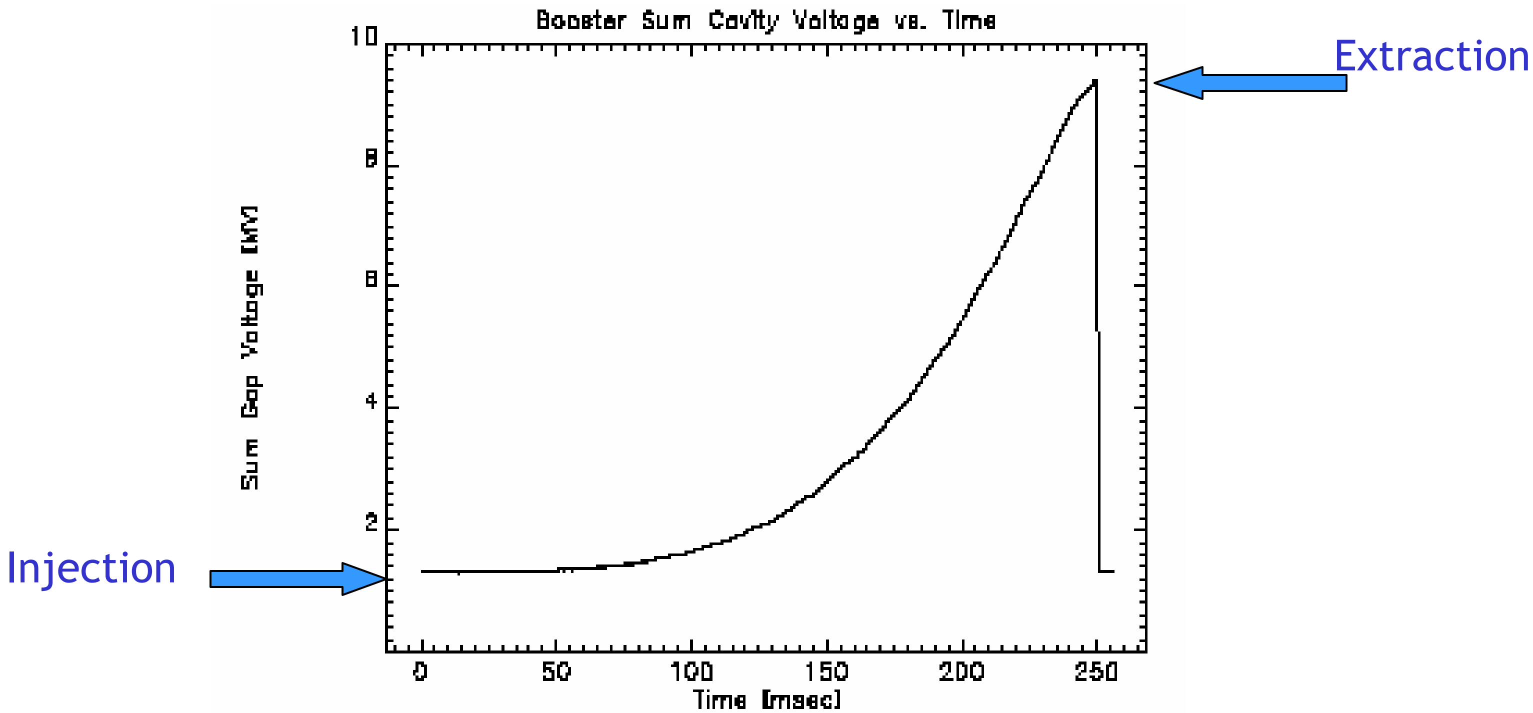
Booster Synchrotron

Circumference	368 m
Revolution time	1.228 μs
Max attainable energy	7.7 GeV
Injection energy	400 MeV
Cycle period	500 ms
Acceleration time	250 ms
Average beam current	4.7 mA
Nominal charge per cycle	5.4 nC
Bunch Length, RMS @7GeV	24 mm
Injected beam emittance	0.36 mm-mrad
Natural emittance at 7 GeV	0.13 mm-mrad
Energy loss/turn at 7 GeV	6.3 MeV/turn
RF gap voltage at 7 GeV	8.3 MV

Booster Synchrotron



Booster Synchrotron



Total sum rf gap voltage as a function of time during energy ramp

RF Bucket

- When beam is captured by the RF system, it is contained in an **RF Bucket**

- Since the cavity is a resonating structure at a specific RF frequency, standing waves are generated within the structure.

- These standing wave "pockets" are the RF buckets

- These buckets do not have to contain beam.

RF Bucket

- If the RF bucket contains beam, then the particles contained within the bucket is referred to as a bunch.

- Harmonic number (h) describes number of possible bucket (bunches) in the an accelerator.

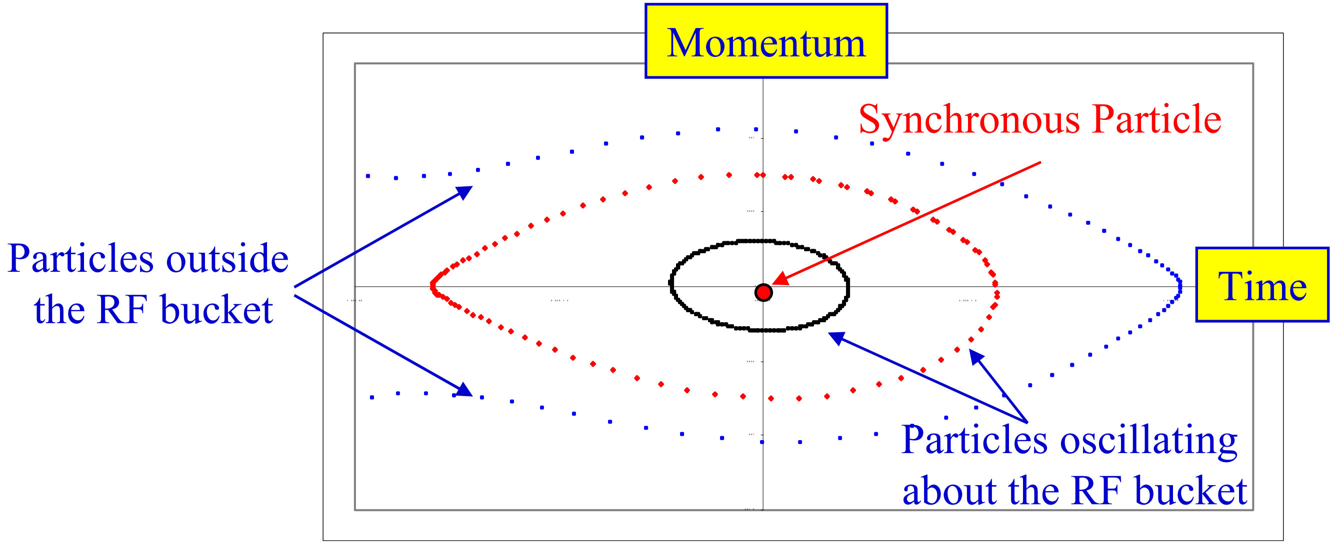
For the APS:

h=1296 for the Storage Ring.

h=432 for the Booster.

Synchrotron Oscillations

- Synchrotron oscillations have the effect of spreading out the particles in the stable region of the RF bucket.
- Increasing the longitudinal emittance.



How Much RF Is Needed?

- RF must:
  - Provide the voltage to accelerate the Beam, providing a good lifetime and reasonable energy acceptance.
  - Replace the energy lost by the Beam due to synchrotron radiation.

Energy Loss due to Radiation

Energy Loss/Turn

$$U_b = \frac{88.5 E_0^4}{\rho}$$

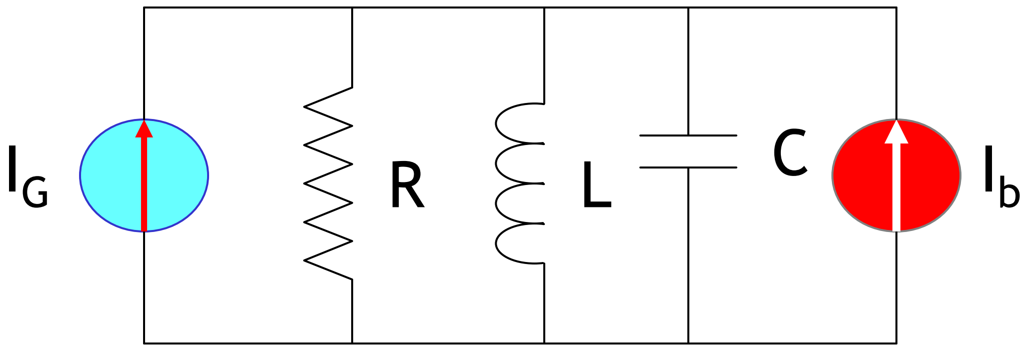
where:

E_o = Beam Energy (GeV),

ρ = Magnet Bending Radius (m).

Beam Loading

The passage of intense beam through an RF cavity induces image wall current which affects the cavity voltage. The beam itself will be affected by the variation of cavity voltage.



$$V = Z(s)I = \frac{s/C}{s^2 + \frac{1}{RC}s + \frac{1}{LC}} I$$

$$\omega_R = \frac{1}{\sqrt{LC}} \qquad \Gamma = \frac{1}{2RC}$$

$$Z(s) = \frac{2\Gamma R s}{s^2 + 2\Gamma s + \omega_R^2}$$

In the vector form, the cavity impedance can be written as

$$Z = R\cos\phi e^{-j\phi}$$

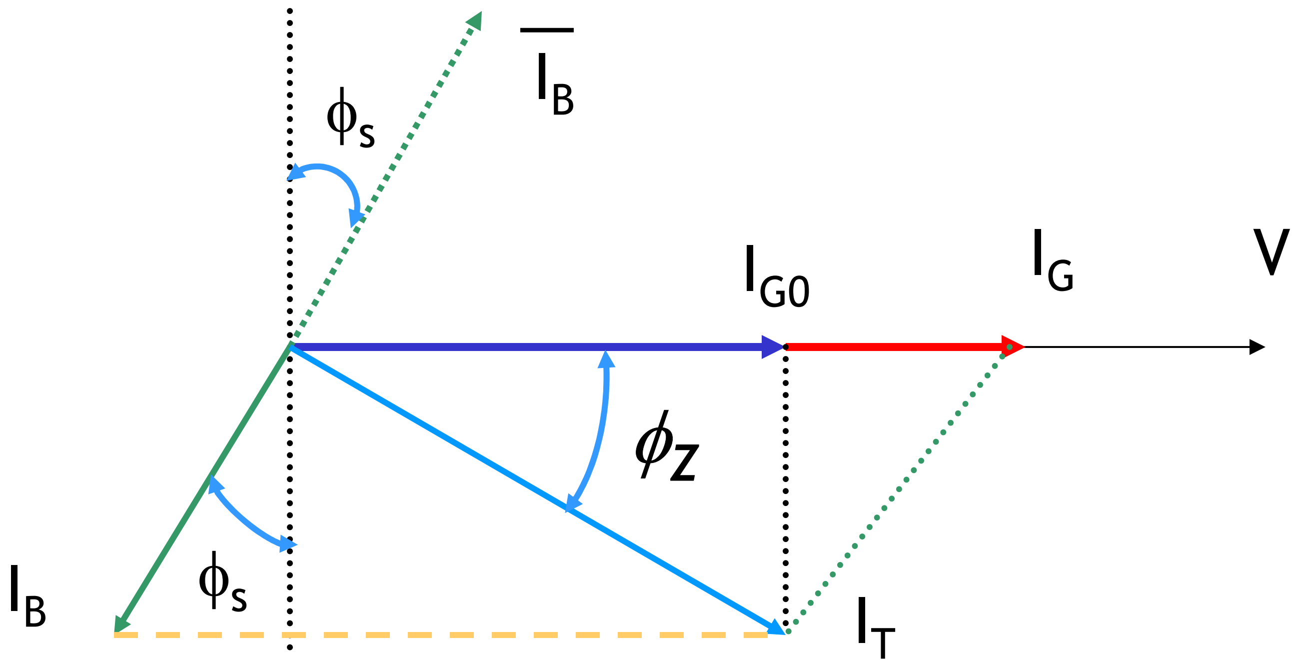
$$\phi = \tan^{-1}\left(Q\left(\frac{\omega_R}{\omega} - \frac{\omega}{\omega_R}\right)\right) \qquad Q = R\sqrt{\frac{C}{L}}$$

Beam Loading

If $\Delta\omega = \omega_R - \omega << \omega_R$,

$$\phi = tan^{-1}\left(2Q\frac{\Delta\omega}{\omega_R}\right) \Rightarrow Z = \frac{R}{1 + j2Q\,\Delta\omega/\omega_R}$$

In the absence of beam, the cavity is driven by I_{G0} with the cavity voltage $V=I_{G0}R$.



Beam Loading

$$\left| I_T R \cos\phi_z e^{-j\phi_z} \right| = V = I_{G0} R \quad \Longrightarrow \quad I_T \cos\phi_z = I_{G0}$$

From beam loading diagram, we have $I_B e^{-j\left(\frac{\pi}{2}+\phi_s\right)} + I_G = I_T e^{-j\phi_z}$

$$\Longrightarrow \quad \begin{aligned} &\tan\phi_z = Y \cos\phi_s \\ &I_G = I_{G0} + I_B \sin\phi_s \end{aligned}$$

Where the ratio of the beam current to the generator current is defined as

$$Y = \frac{I_B}{I_G}$$

Beam Loading

Robinson Stability Criteria

$$\Delta\phi_B = T(s)\Delta\phi_C = \frac{\Omega_s^2}{s^2 + \Omega_s^2}\Delta\phi_C$$

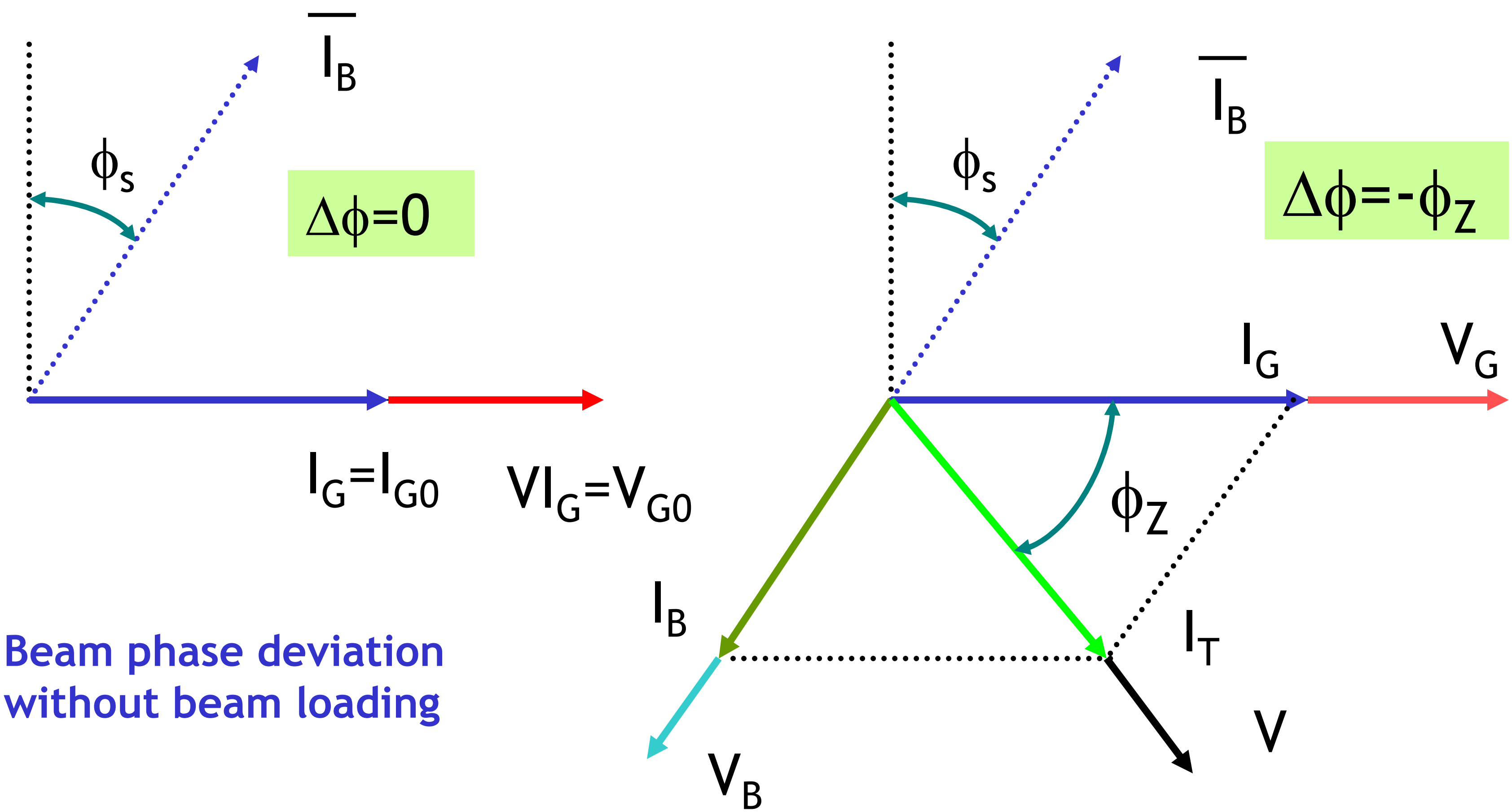
The beam loading can be represented by the reaction of the cavity voltage to the beam current. If the cavity is detuned by a large amount, then this reaction has both phase and amplitude effects.

To guarantee the stability

$tan\phi_Z > 0$ → 1st Robinson Criteria

$Y\, tan\phi_Z\, cos^2\phi_Z < cos\phi_Z$ → 2nd Robinson Criteria

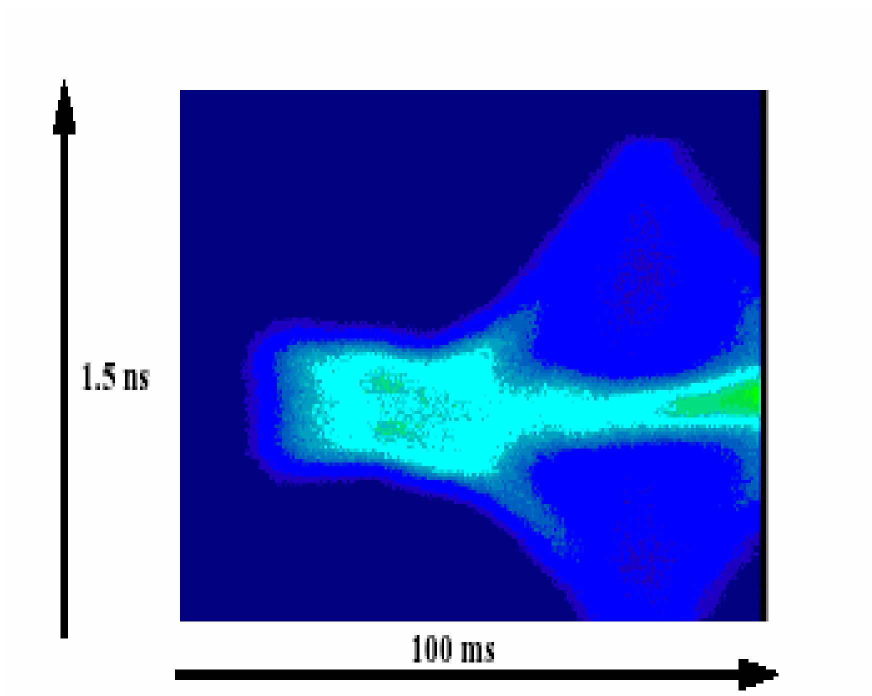
Beam Loading



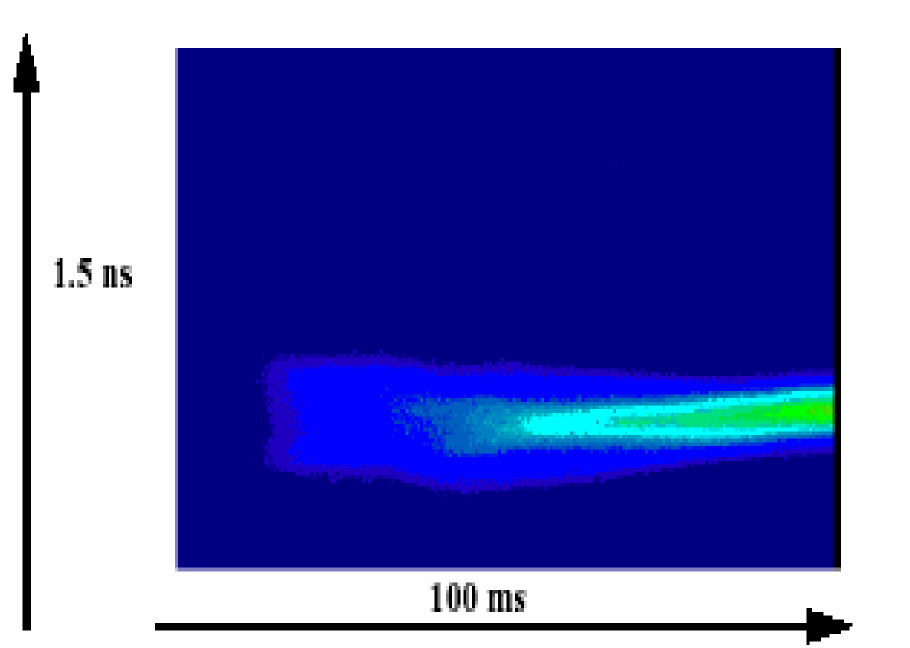
Beam phase deviation without beam loading

Beam phase deviation with beam loading

Beam Loading



Longitudinal bunch distribution vs. time in the booster during a beam loading episode.



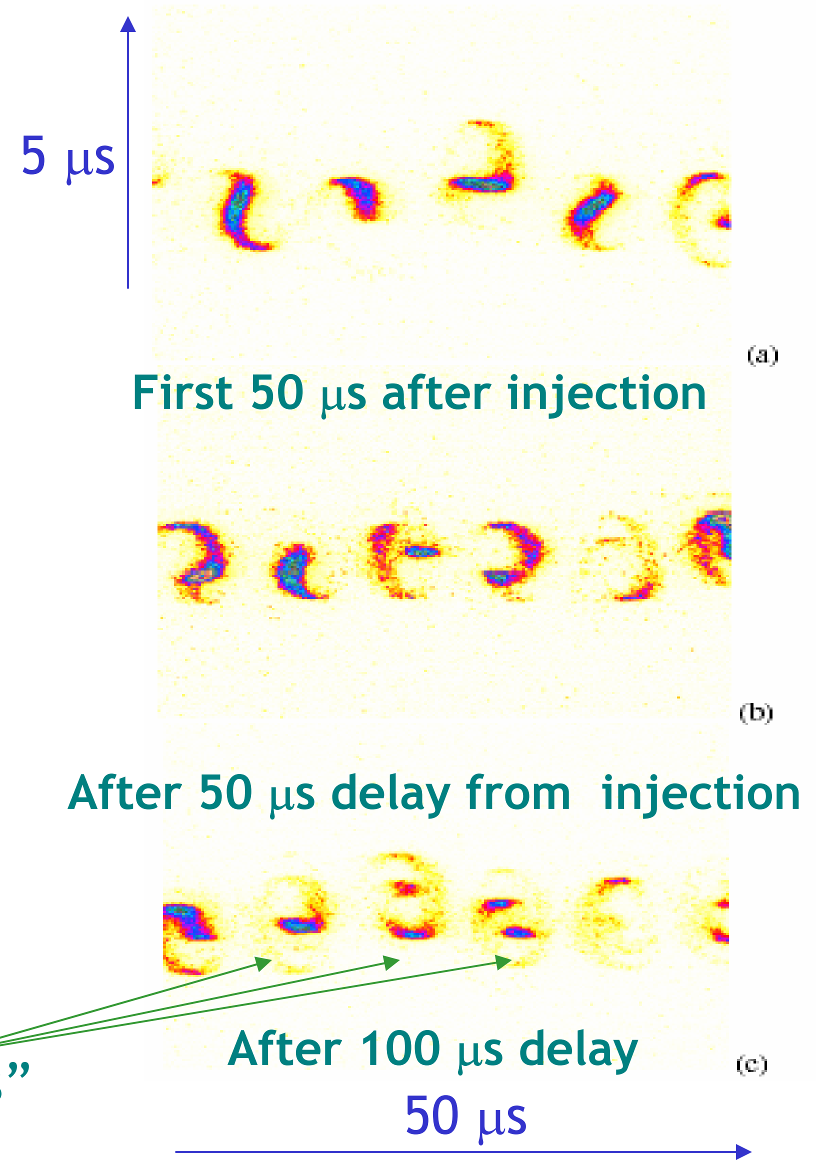
Longitudinal bunch distribution vs. time. Initial beam loading is compensated.

“Yang, Nassiri,Harkay”

Booster Synchrotron

Period of synchrotron oscillation ~25 μs

Synchrotron Frequency of 30 kHz



First 50 μs after injection

After 50 μs delay from injection

After 100 μs delay

"doughnuts"

Decoherence due to nonlinear effective potential within the first 150 μs (125 turns)

"Yang, Nassiri,Harkay,"

Booster Synchrotron

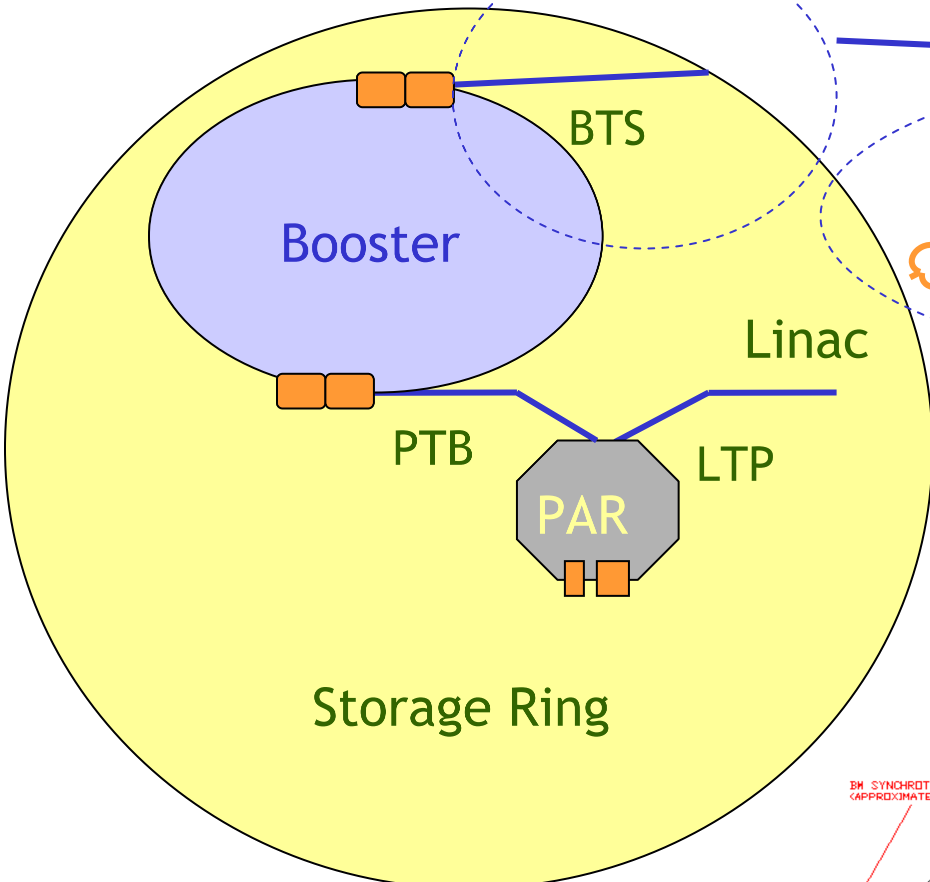
First 50 ms after injection

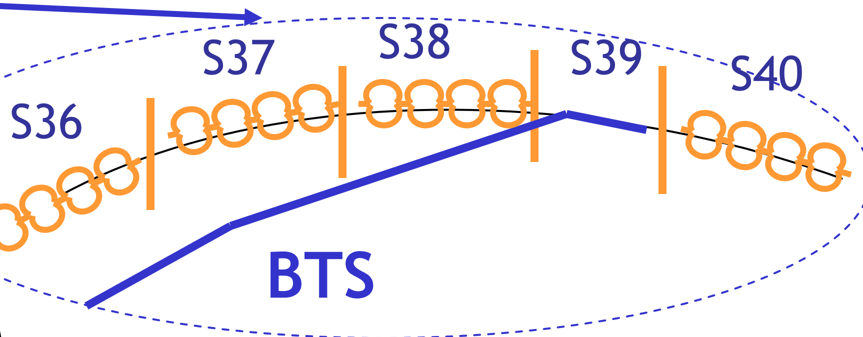
After 50 ms delay from injection

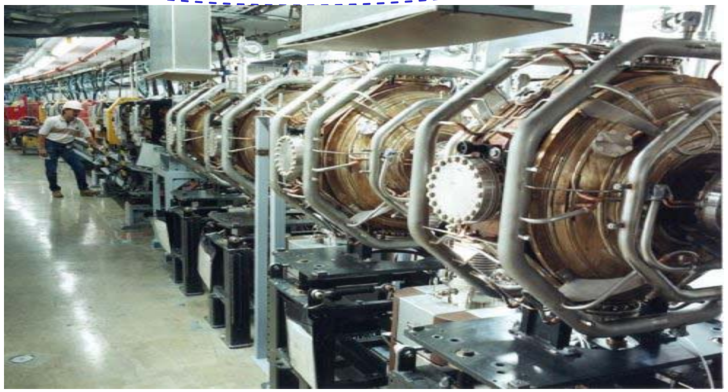
As the beam is accelerated during the ramp period, the size of the "doughnuts" decreases due to increase synchrotron radiation damping.

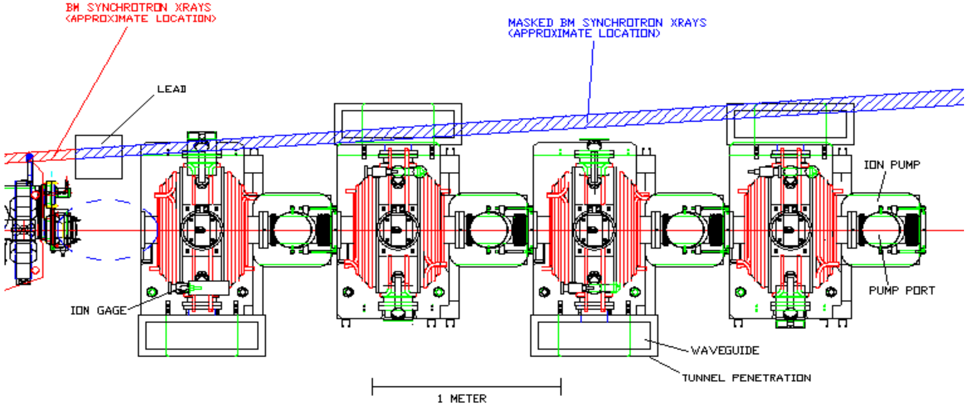
"Yang, Nassiri,Harkay,"

Storage Ring









HARMONIC NUMBER, BUCKETS & BUNCHES

- The voltage per turn given to the synchronous particle is

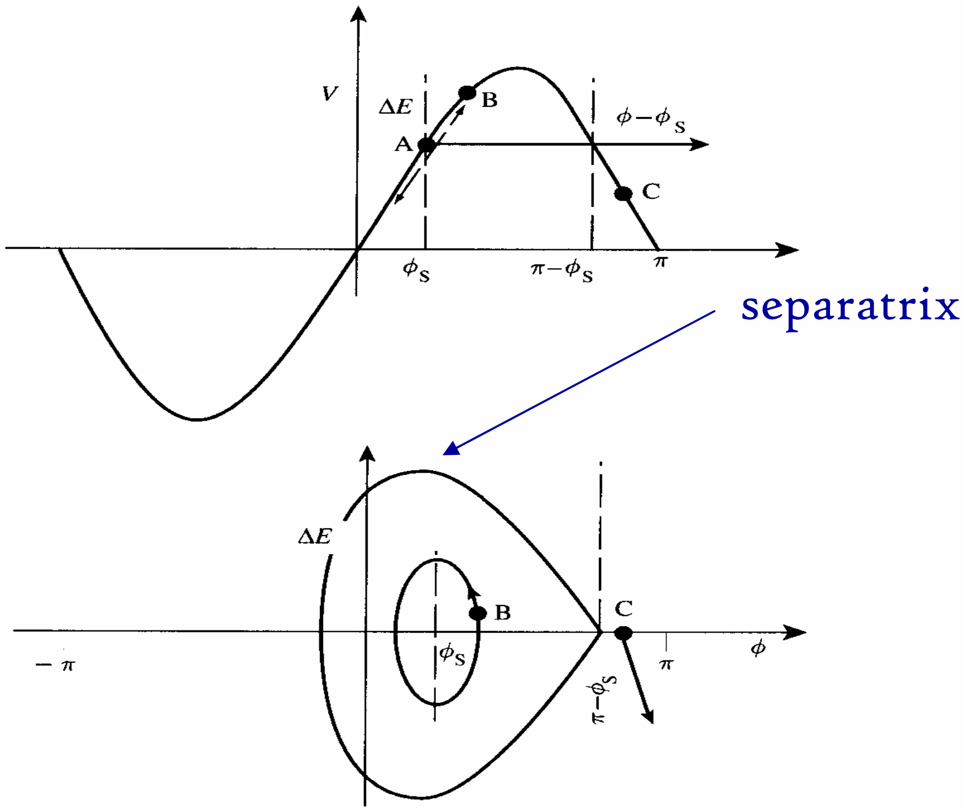
$$V_s = V_0 \sin(\phi_s)$$

- For the synchronous particle to arrive with constant phase, the r.f. frequency must be an integer multiple of the orbit frequency, known as *h*, the harmonic number

$$f_a = hf$$

- The h segments circulating around the ring where a particle bunch can be centered at the synchronous phase are called buckets

STABILITY BOUNDS FOR LARGE ENERGY/TIME OFFSETS

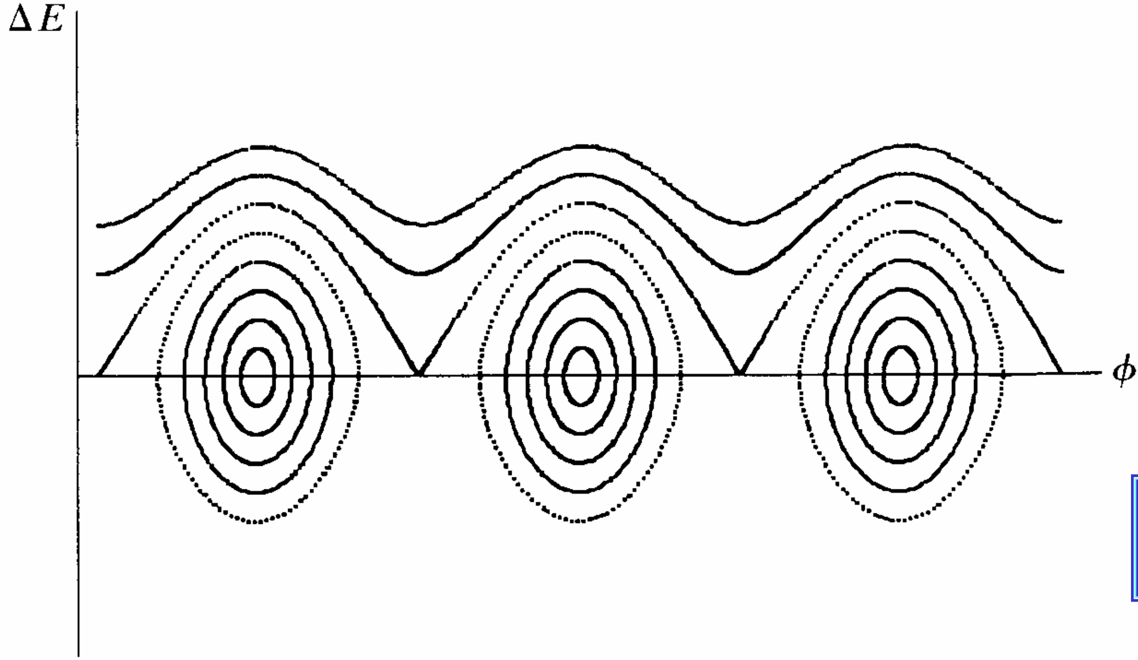


There is a limiting trajectory in phase space inside of which a particle will be longitudinally focused. This boundary is known as a separatrix.

Scanned figure from *Edmund Wilson, "An Introduction to Particle Accelerators", 2001, Oxford University Press.*

PURE FOCUSING

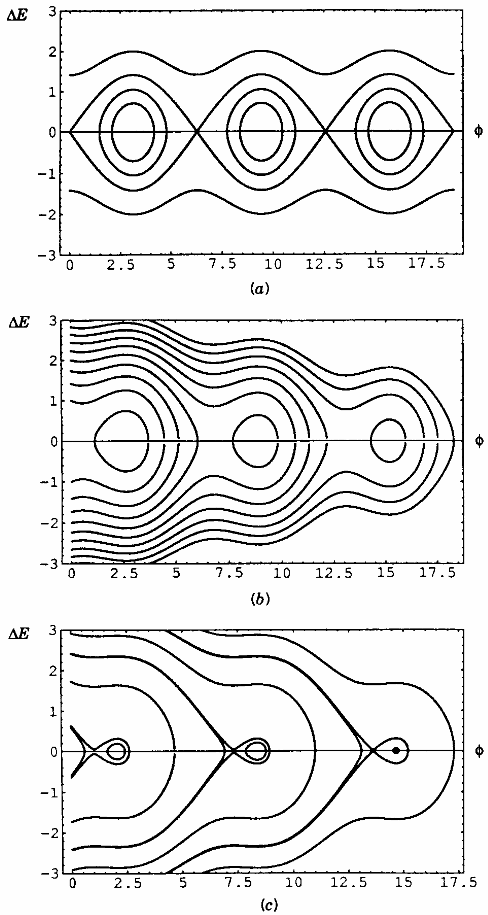
Even when the beam is coasting, storage rings use some rf acceleration to maintain longitudinal focusing. When the ideal particle is not accelerated, the stable regions are called stationary buckets.



$$\phi_s = 0, \pi$$

Scanned figure from D.A. Edwards and M.J. Syphers, "An Introduction to The Physics of High Energy Accelerators, 1993, Wiley

THE TRADE-OFF BETWEEN ACCELERATION & PHASE STABILITY



$$\phi_s = \pi$$

$$\phi_s = 5\pi / 6$$

$$\phi_s = 2\pi / 3$$

Scanned figure from D.A. Edwards and M.J. Syphers, "An Introduction to The Physics of High Energy Accelerators, 1993, Wiley

Acceleration

- Important concepts in rings:
  - Revolution period τ
  - Revolution frequency ω

$$\tau = \frac{2\pi R}{v} \approx \frac{L}{c}$$

$$\omega = \frac{1}{\tau} \approx \frac{c}{L}$$

- If several bunches in machine, introduce RF cavities in straight sections with oscillating fields
  - h is the harmonic number.

$$\omega_{rf} = h\omega = \frac{hc}{L}$$

$$\rho = \left|\frac{p}{qB}\right|$$

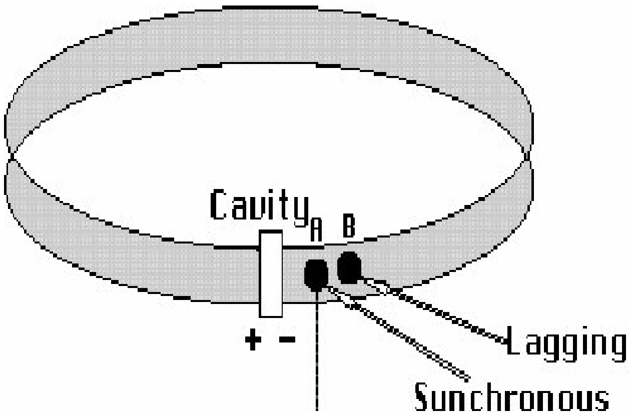
- Energy increase ΔE when particles pass RF cavities

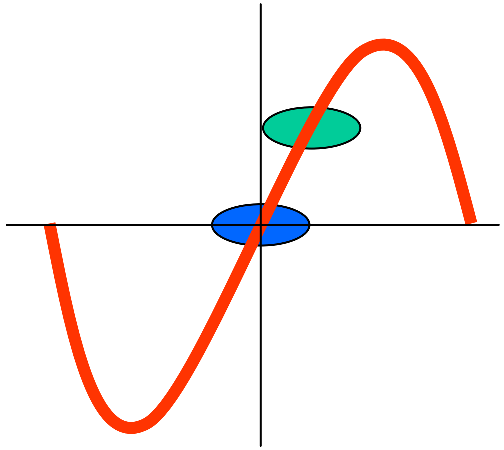
$\Rightarrow$ can increase energy only so far as can increase B-field in dipoles to keep constant ρ.

Magnetic Rigidity

$$B\rho = \frac{p}{q}$$

Effect on Particles of an RF Cavity





Bunching Effect

- Cavity set up so that centre of bunch, called the synchronous particle, acquires just the right amount of energy.
- Particles see voltage $V_0 \sin 2\omega_{rf} t = V_0 \sin\phi\,(t)$
  - In case of no acceleration, synchronous particle has $\phi_s = 0$
  - Particles arriving early see $\phi < \phi_s$
  - Particles arriving late see $\phi > \phi_s$
    - $\Rightarrow$ **energy of those in advance is decreased wrt synchronous particle and vice versa.**
- To accelerate, make $0 < \phi_s < \pi$ so that synchronous particle gains energy $\Delta E = qV_0 \sin\phi_s$

Storage Ring

General Parameters

Nominal energy	7GeV
Nominal circulating current, multi-bunch	100 mA
Nominal circulating current, multi-bunch	100 mA
Single bunch current	5-12 mA
Harmonic number (RF buckets available)	1296
Bunch length, rms, natural	5.3 mm
Bunch length, fwhm, max bunch current	72 ps
Filling time, multi-bunch to 100 mA	< 1 min
Synchrotron radiation loss per turn	5.6 MeV

Storage Ring

RF Parameters

RF frequency	351.93 MHz
Peak Voltage (100 mA)	9.4 MV
Number of cavities	16
RF voltage per cavity	580 kV
Number of klystrons	4
Synchrotron frequency	1.94 kHz

Storage Ring

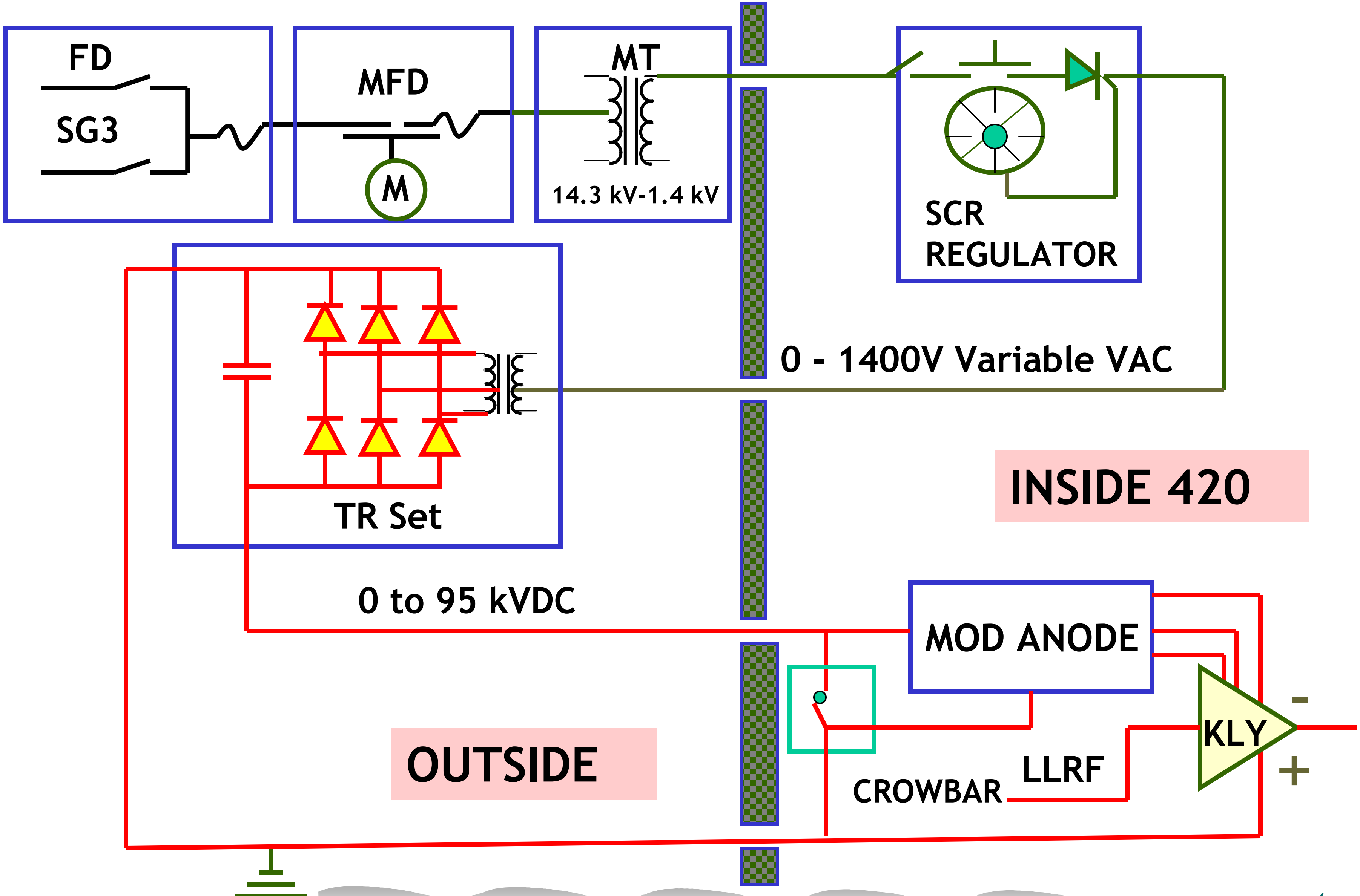
Cavity Parameters

7GeV, 100 mA

Voltage per turn	9.4 MV
Voltage per cavity	580 kV
Power per cavity (nominal)	37 kW
Total power	592 kW
Beam power per cavity	48 kW
Sum power/cavity	85 kW
Loaded Q	21000
Bandwidth (loaded)	17 kHz
3dB bandwidth	7.2 kHz

Storage Ring

HVPS



Storage Ring

The Universal Voltronics high voltage DC power supplies are fed primary input power from 13.2 kV AC lines, which are direct feeds from the 13.2 kV switchgear SG-R3, located near the RF Transformer Pads. The two lines that feed SG-R3 come from building 450.They are CM07 and CM08

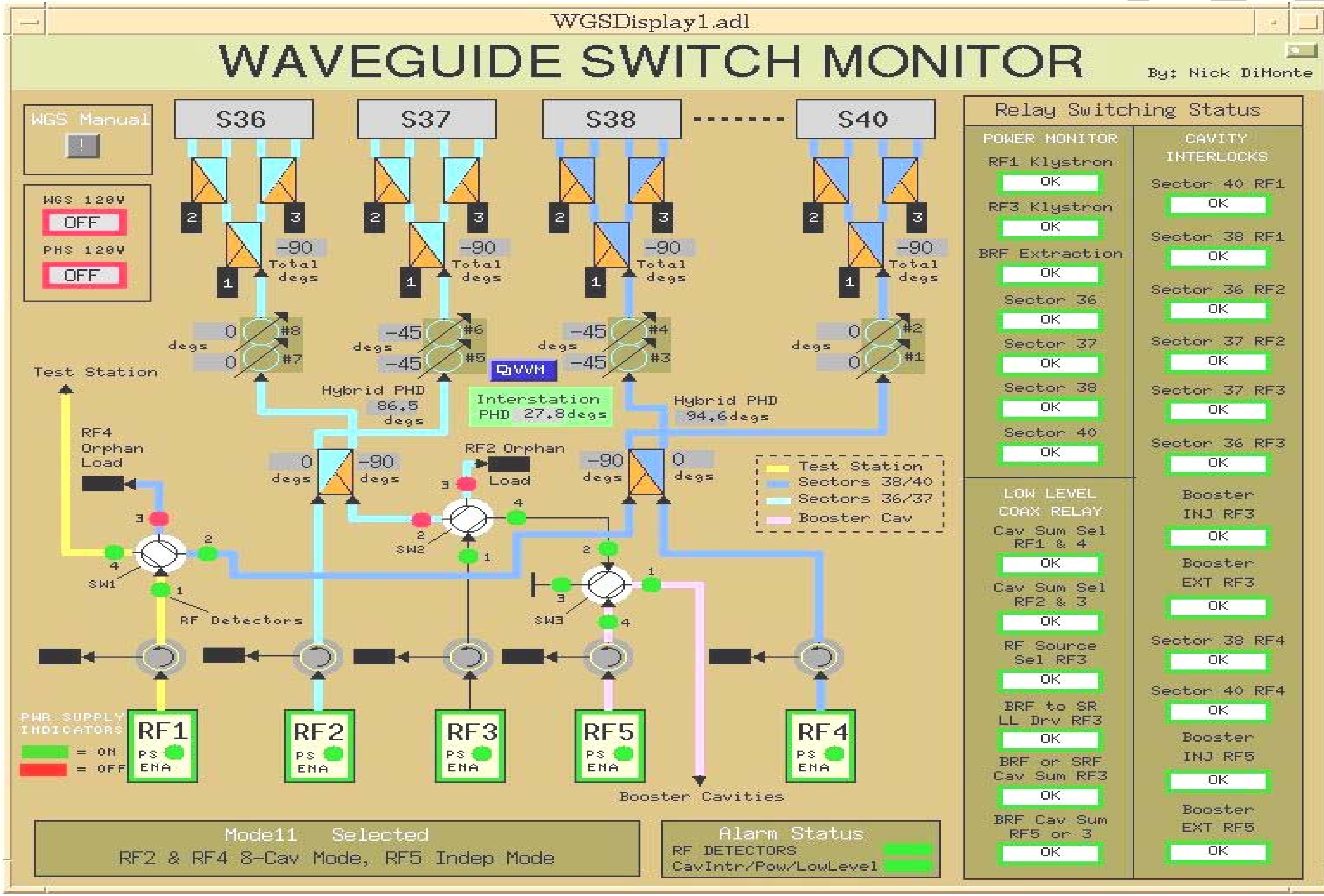
Matching transformers and motorized fused disconnects. They are located outside of building 420 in the infield of the Storage Ring. The fused disconnect has a motor that opens and closes the circuit. It is also a 150 AMP fuse.

Storage Ring

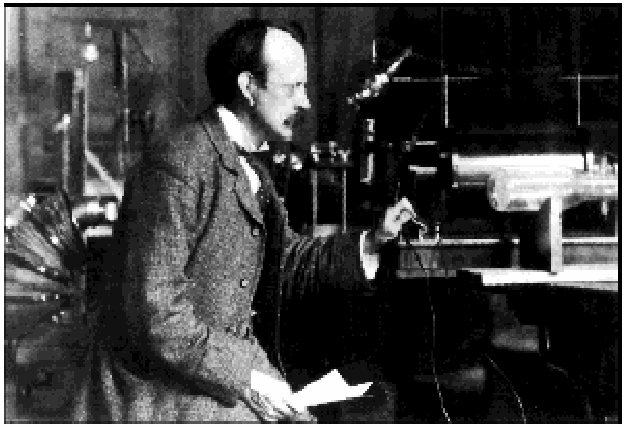
TRANSFORMER/RECTIFIER

SET

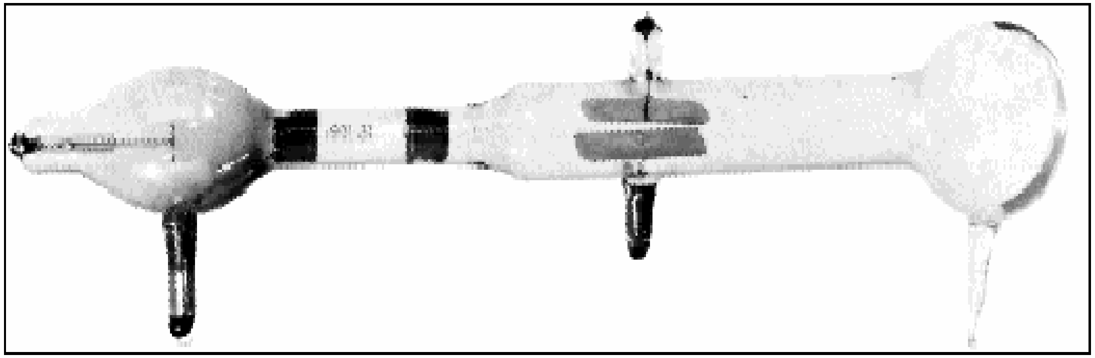
Storage Ring



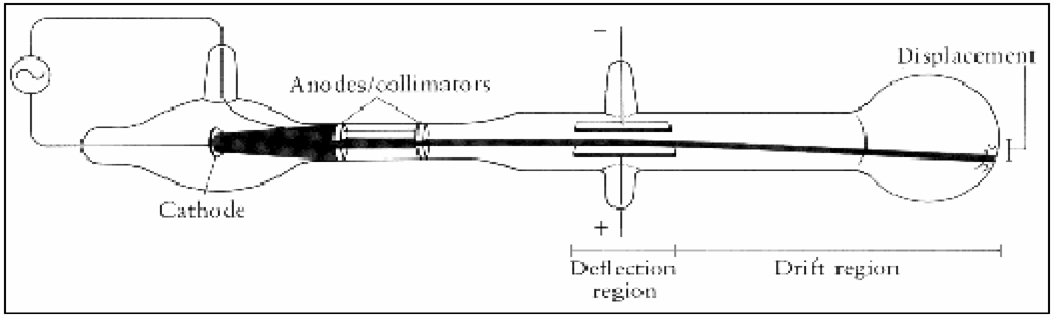
Storage Ring



J.J. Thomson and a cathode ray tube from around1897, the year he announced the discovery of the electron.

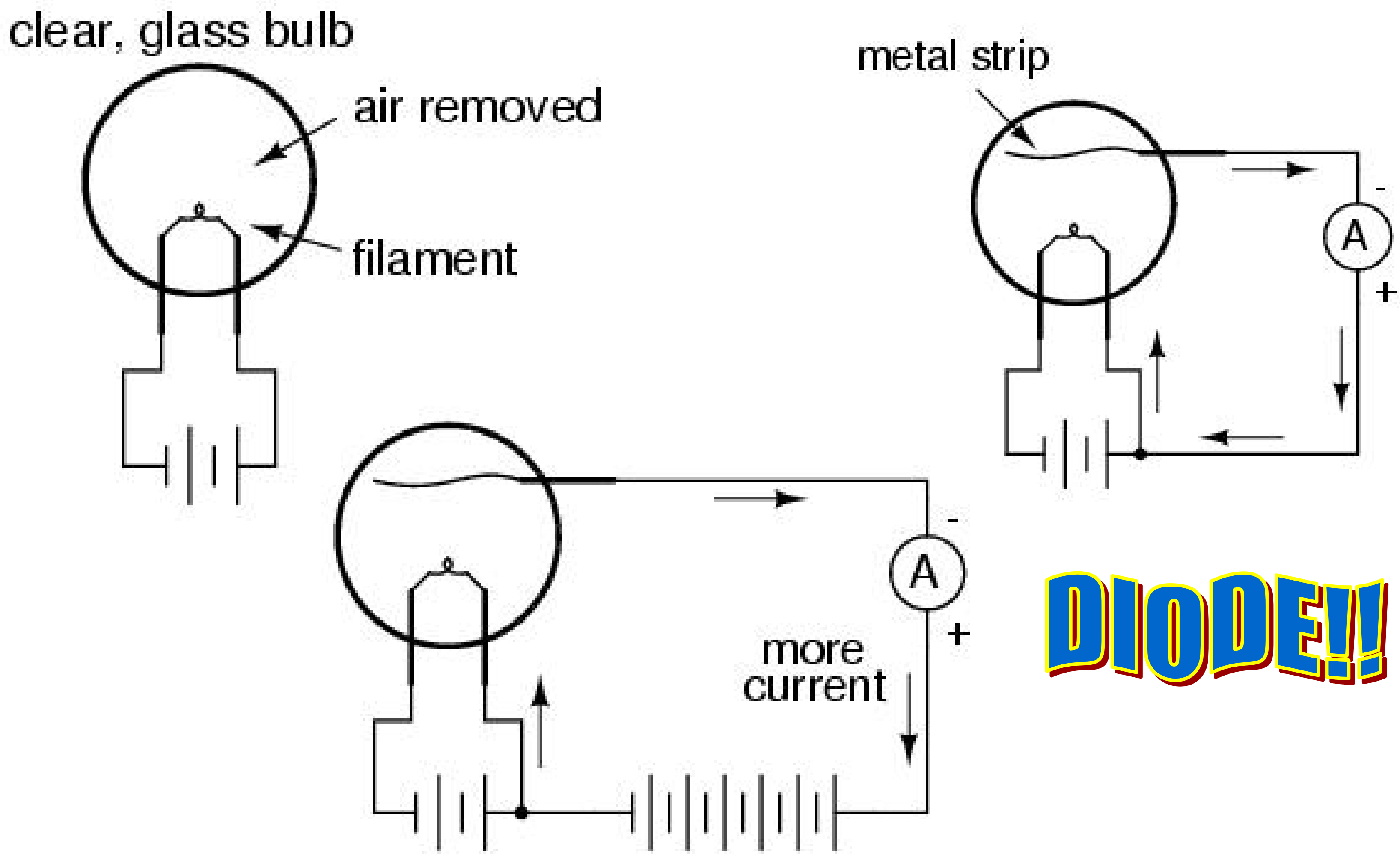


Photograph of one of Thomson's CRT's. The long glass finger projecting downward from the right-hand globe is where the entire tube was evacuated down to as good as a vacuum as could be produced, then sealed.



This diagram appeared in an article by J.J. Thomson in 1897 announcing the discovery of the electron.

Early History…..Edison 1880's



DeForest "Audion" tube 1906

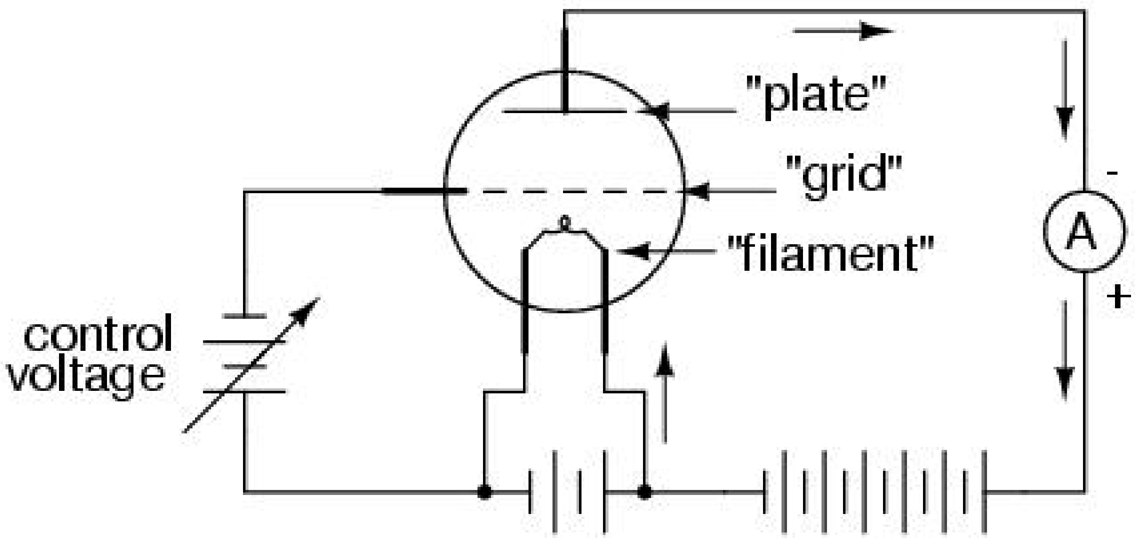
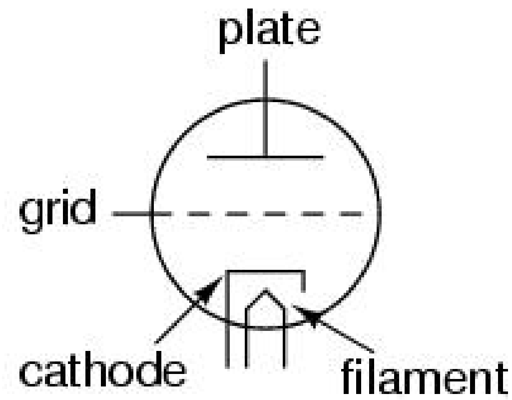
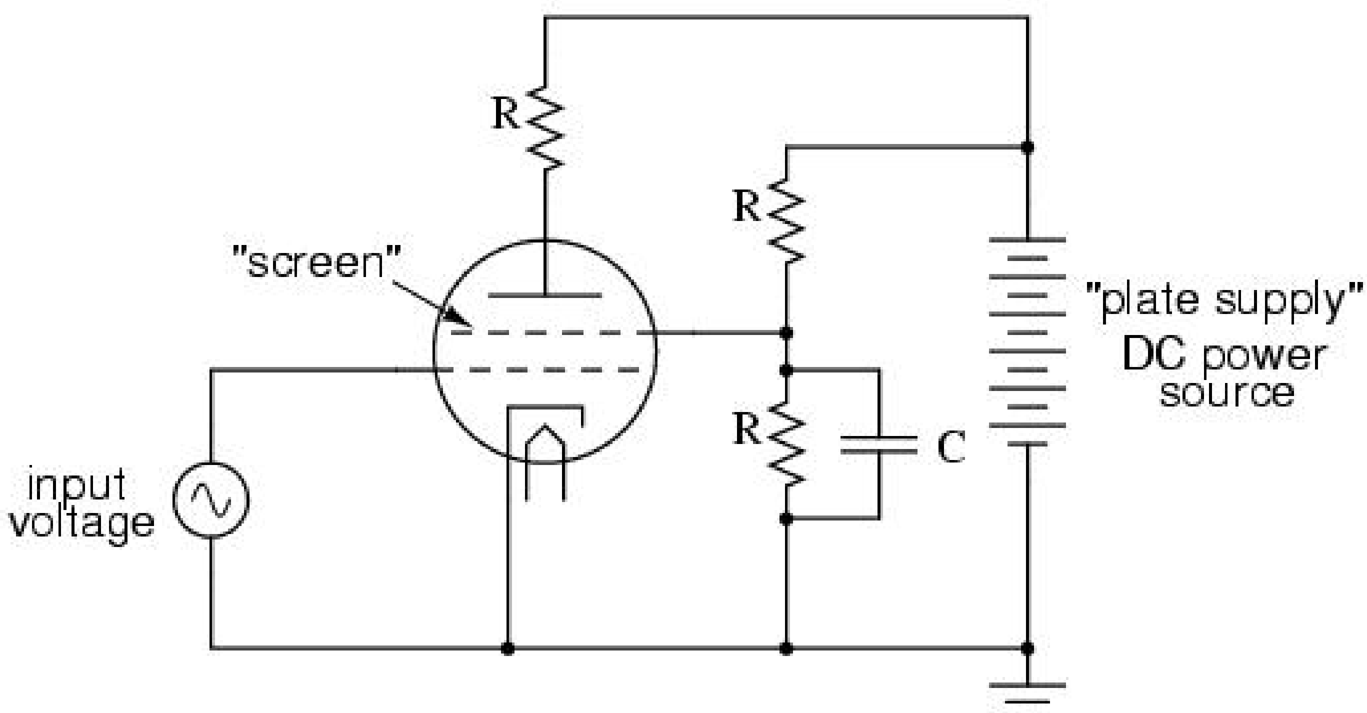


plate current can be controlled by the application of a small control voltage between the grid and filament!

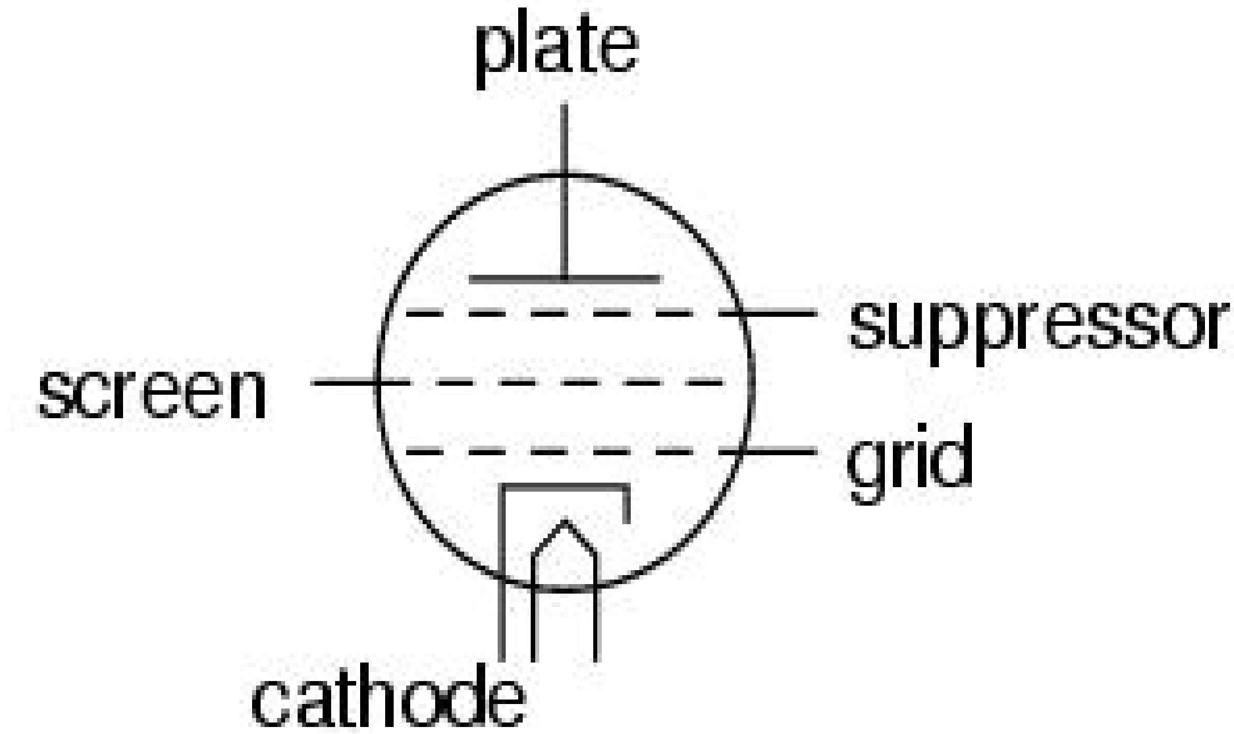


Triode

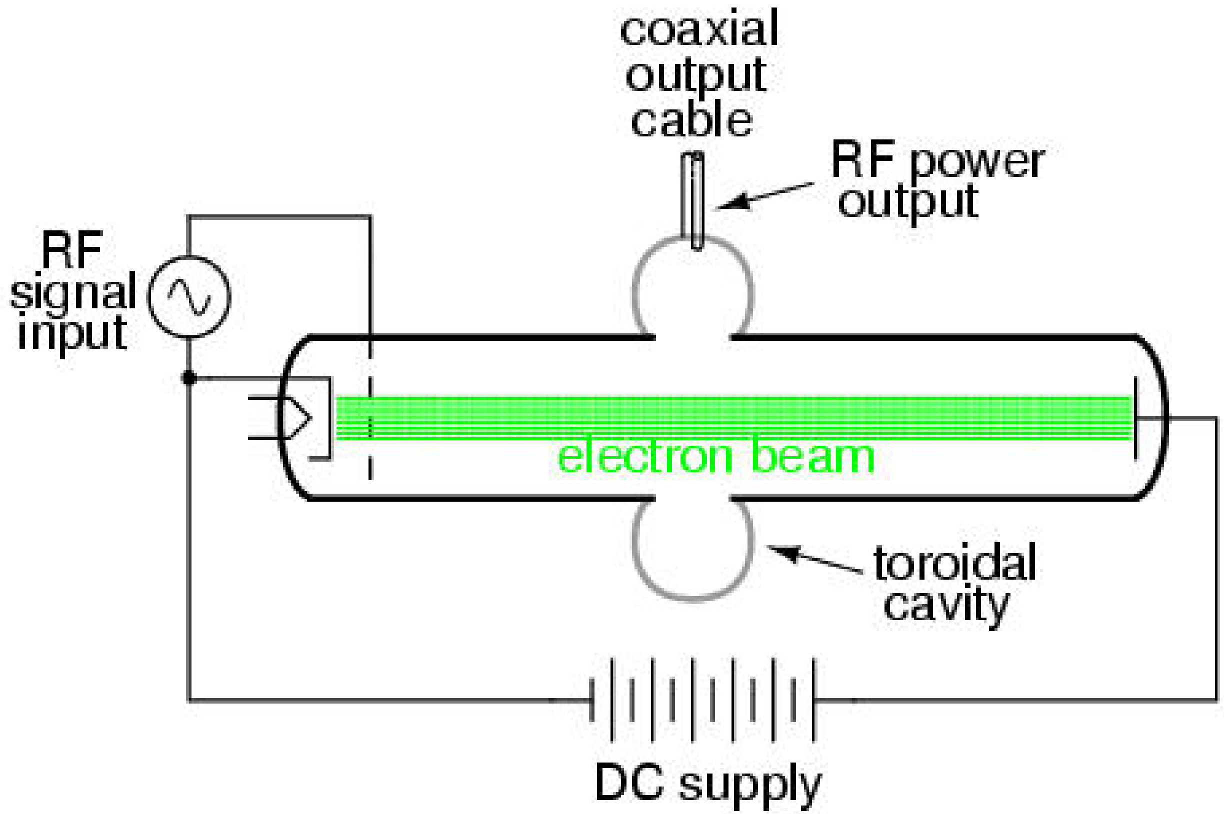
Tetrode Amplifier



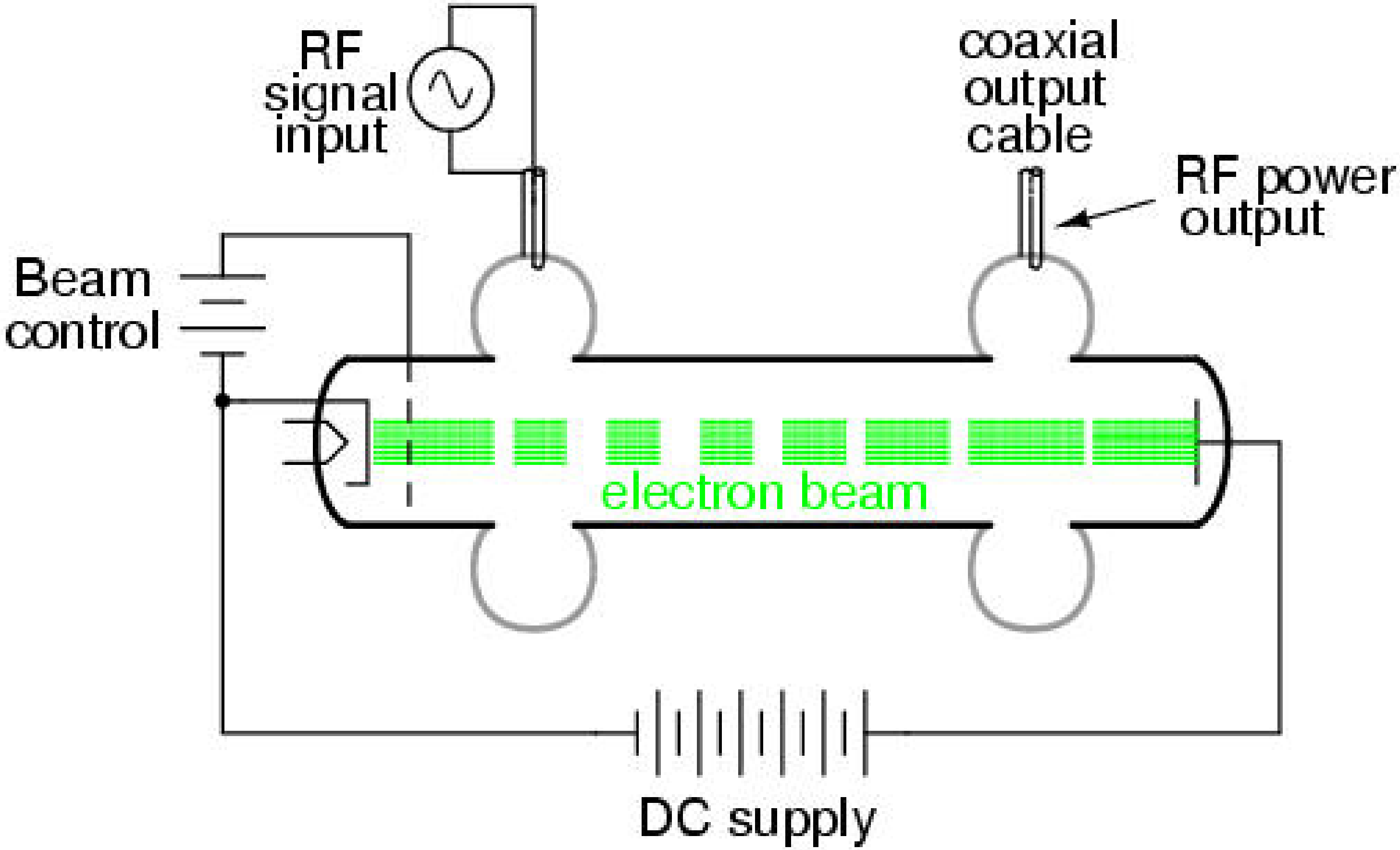
The Pentode Tube



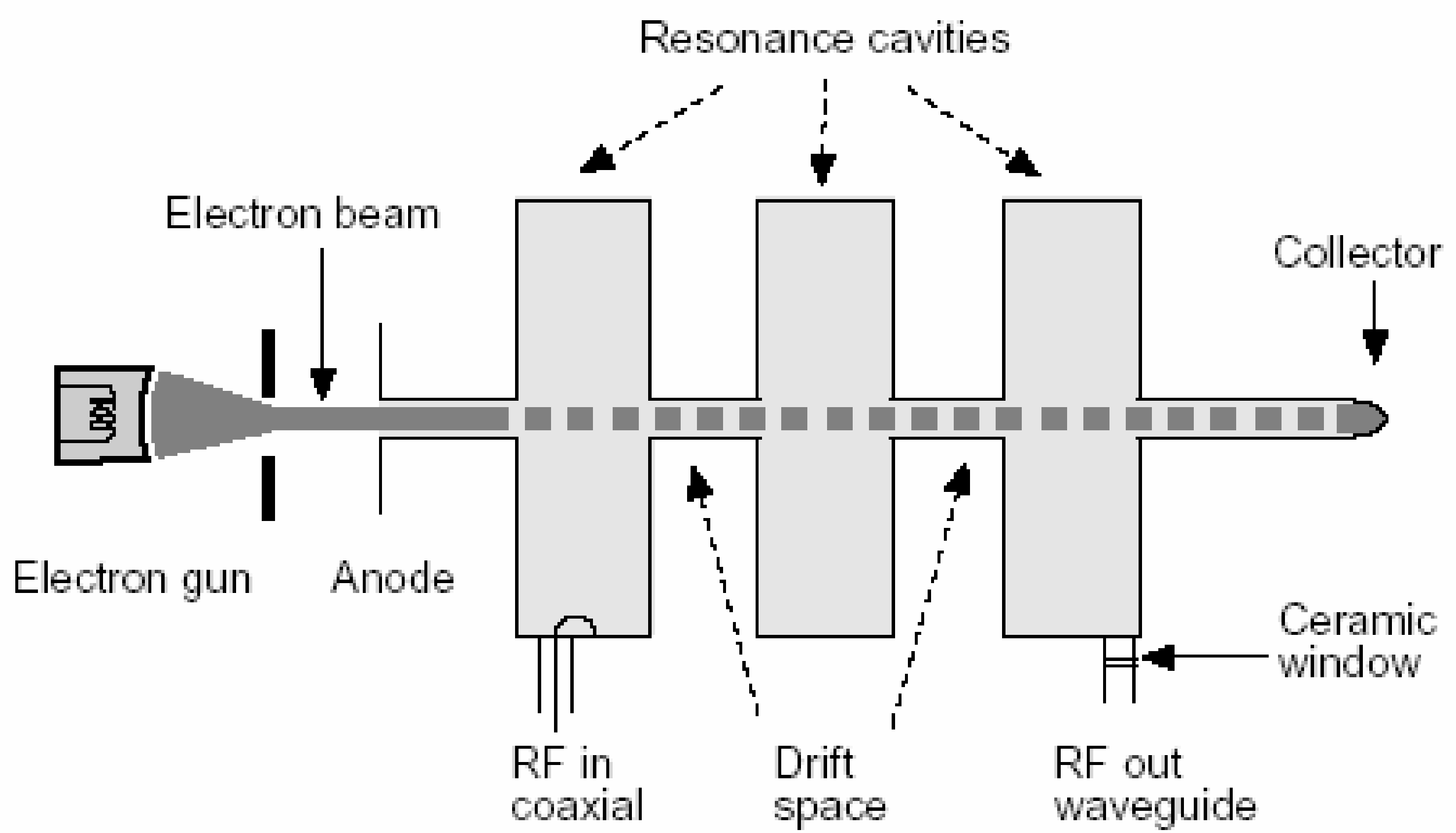
The Inductive Output Tube



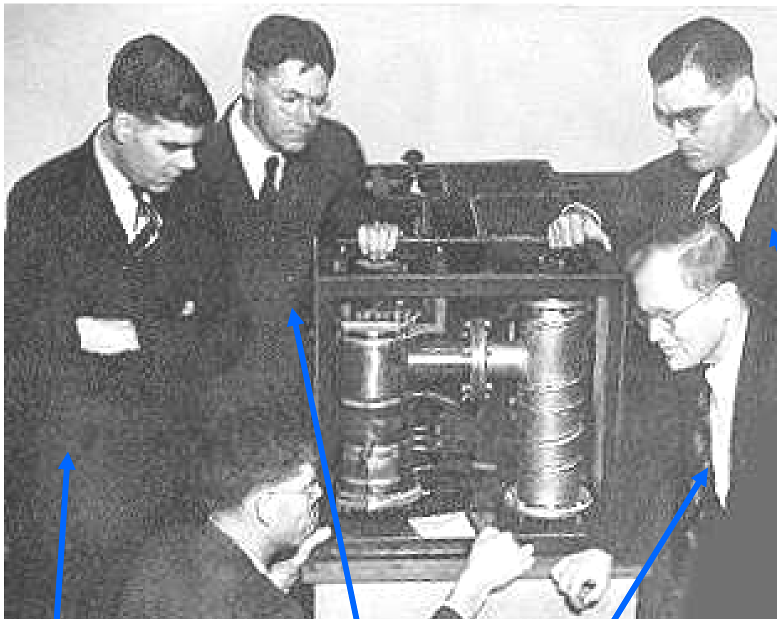
The Klystron Tube



Storage Ring



Klystron



William Hansen

John Woodyard

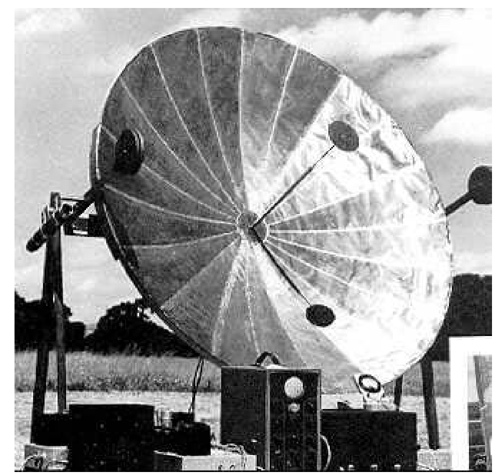
Sig Varian

David Webster

Russ Varian

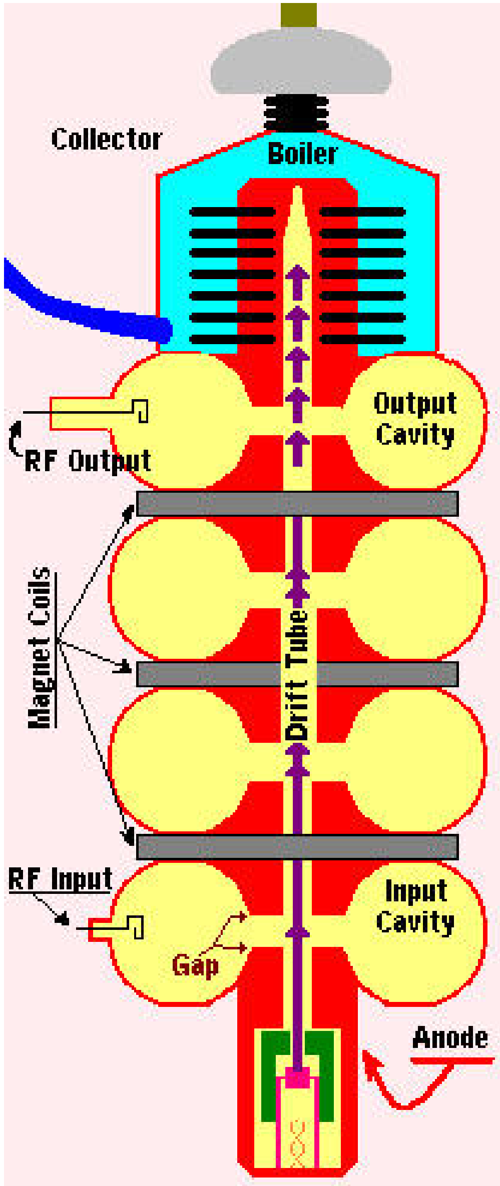
Klystron was invented during the summer of 1937.

Announced to the world on February 1939 (J. Appl Phys).

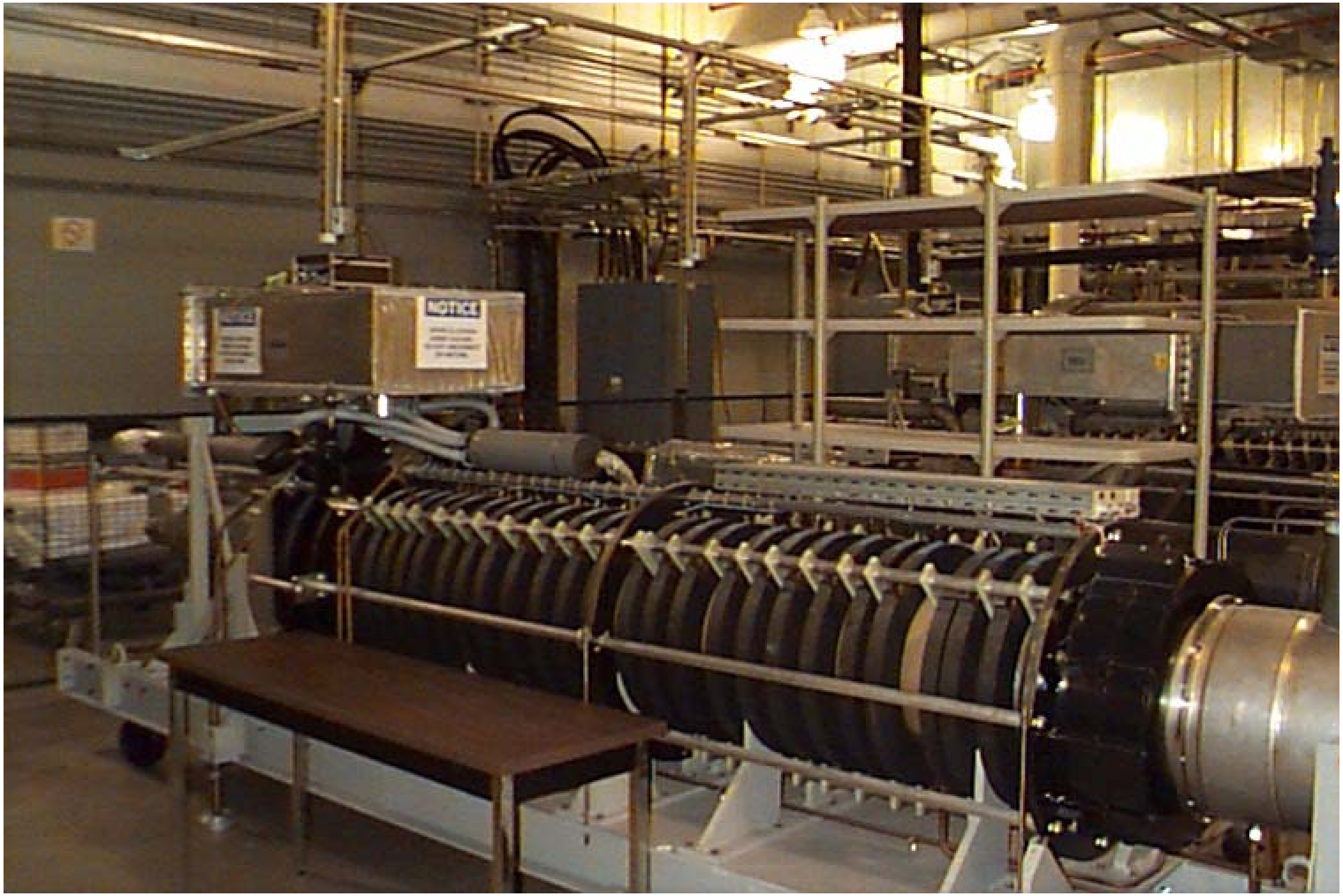


The first microwave radar system, with a klystron acting as the power source.

Inside the Klystron

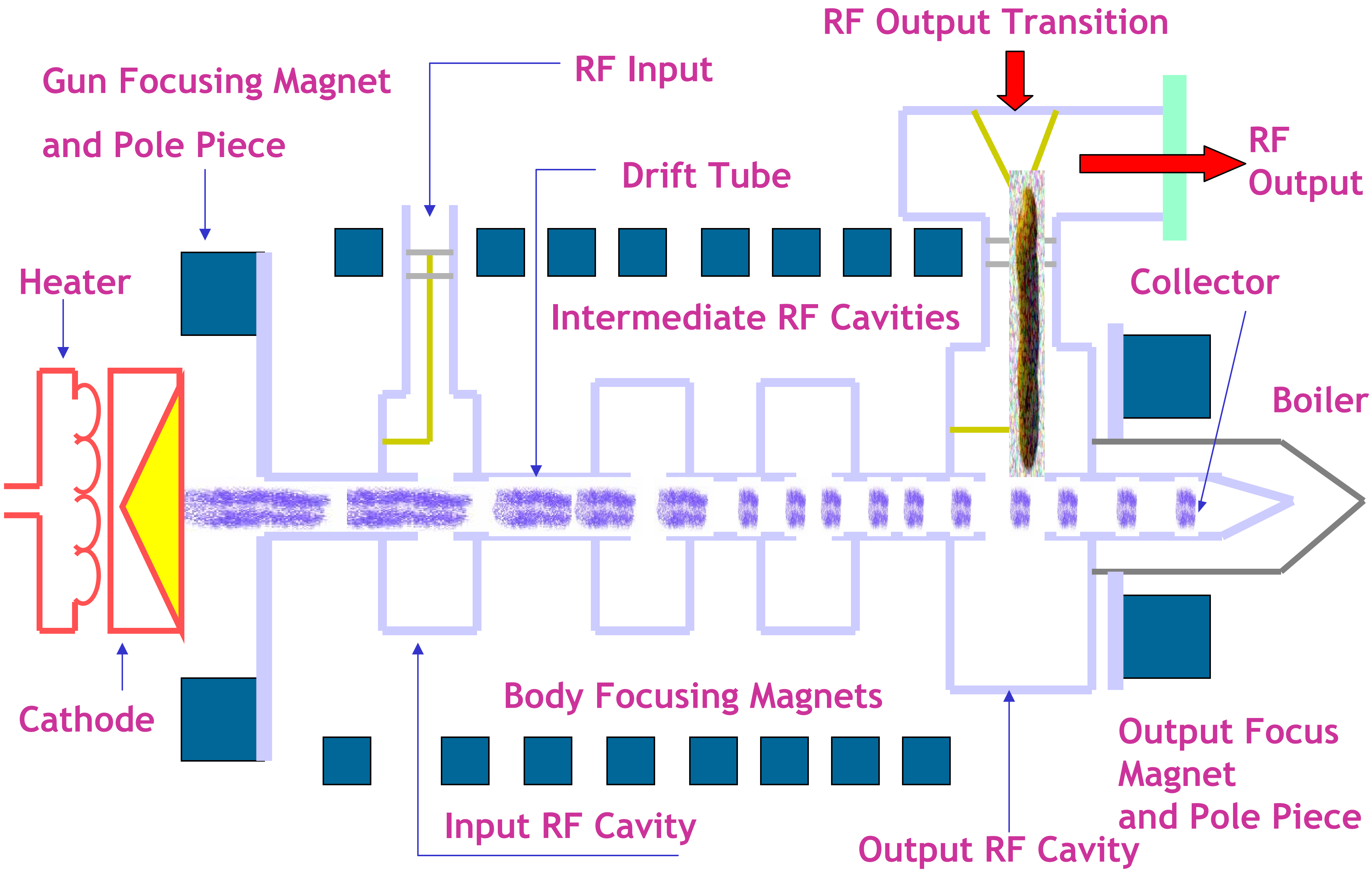


- Cathode produces electrons.
- Voltage pulse from anode to cathode accelerates electrons.
- Magnets are used to focus the electron beam
- Cavities velocity modulate the electron beam
- Output cavity, or ultimate cavity, is coupled to the transmission line
- 5 Cavities is common.
- Cavities tuned to different frequencies to provide required bandwidth.
- Collector must absorb the high energy electrons – must be cooled! Collector must absorb power not removed in the output cavity. Many varieties of collectors exist to dissipate the high heat load of the electrons.

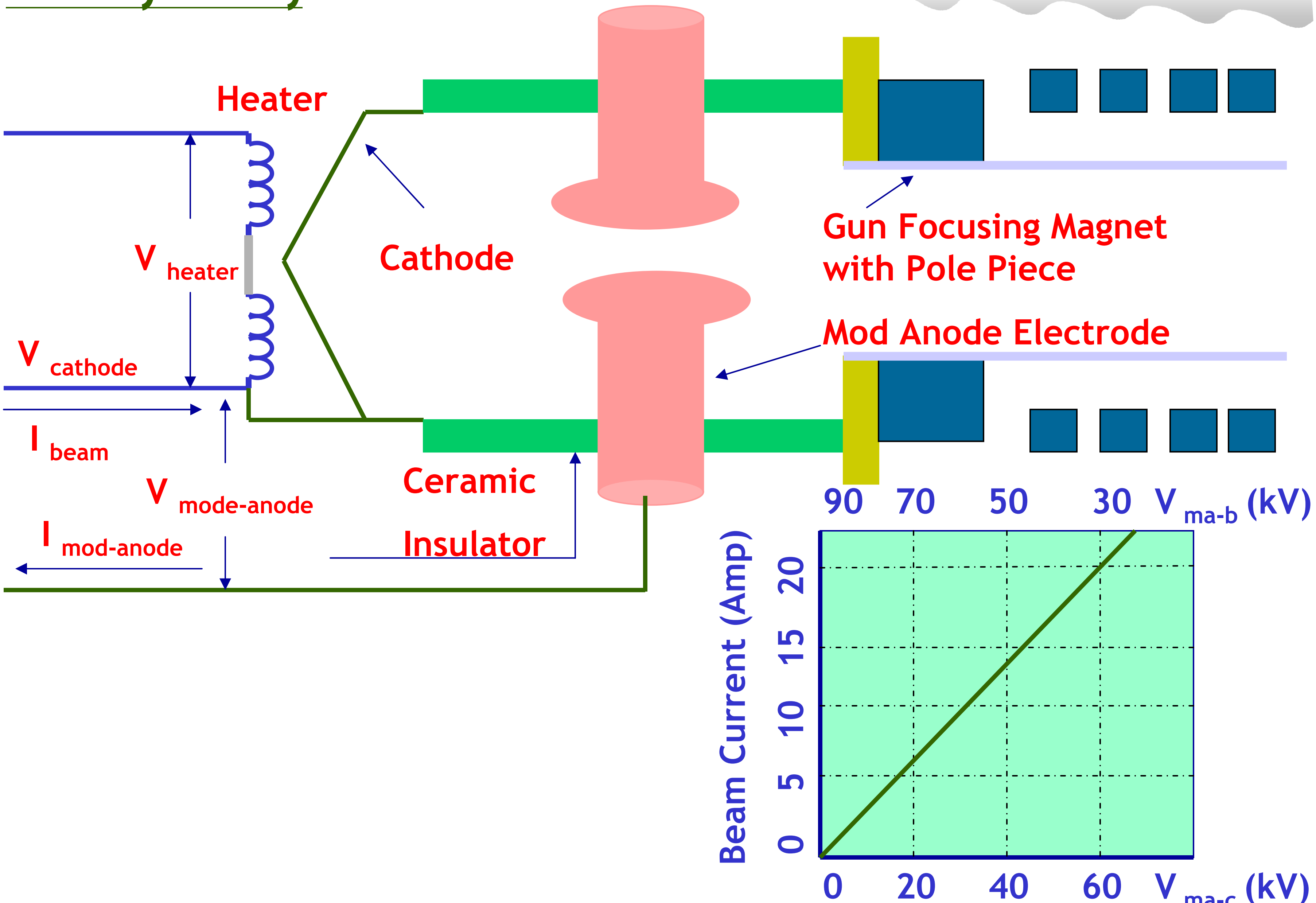


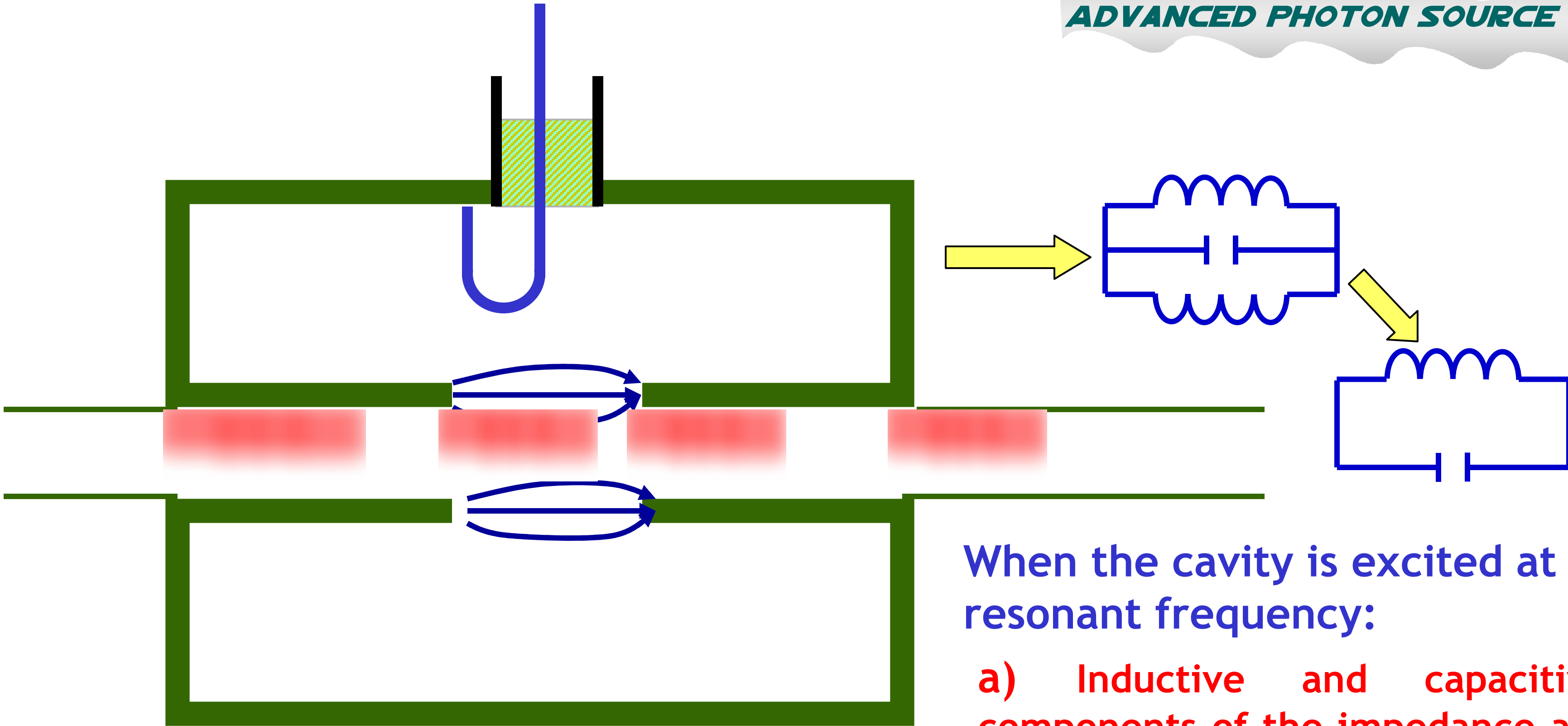
352 MHz Klystron

Storage Ring



Storage Ring



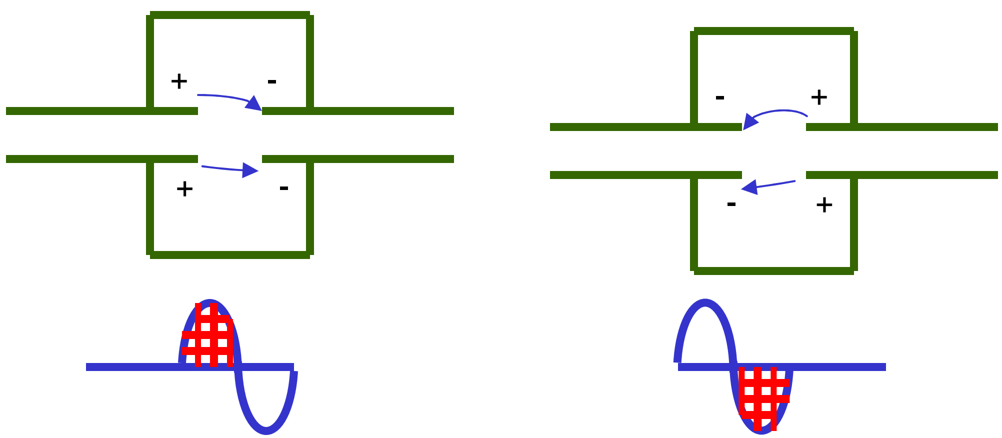


When the cavity is excited at its resonant frequency:

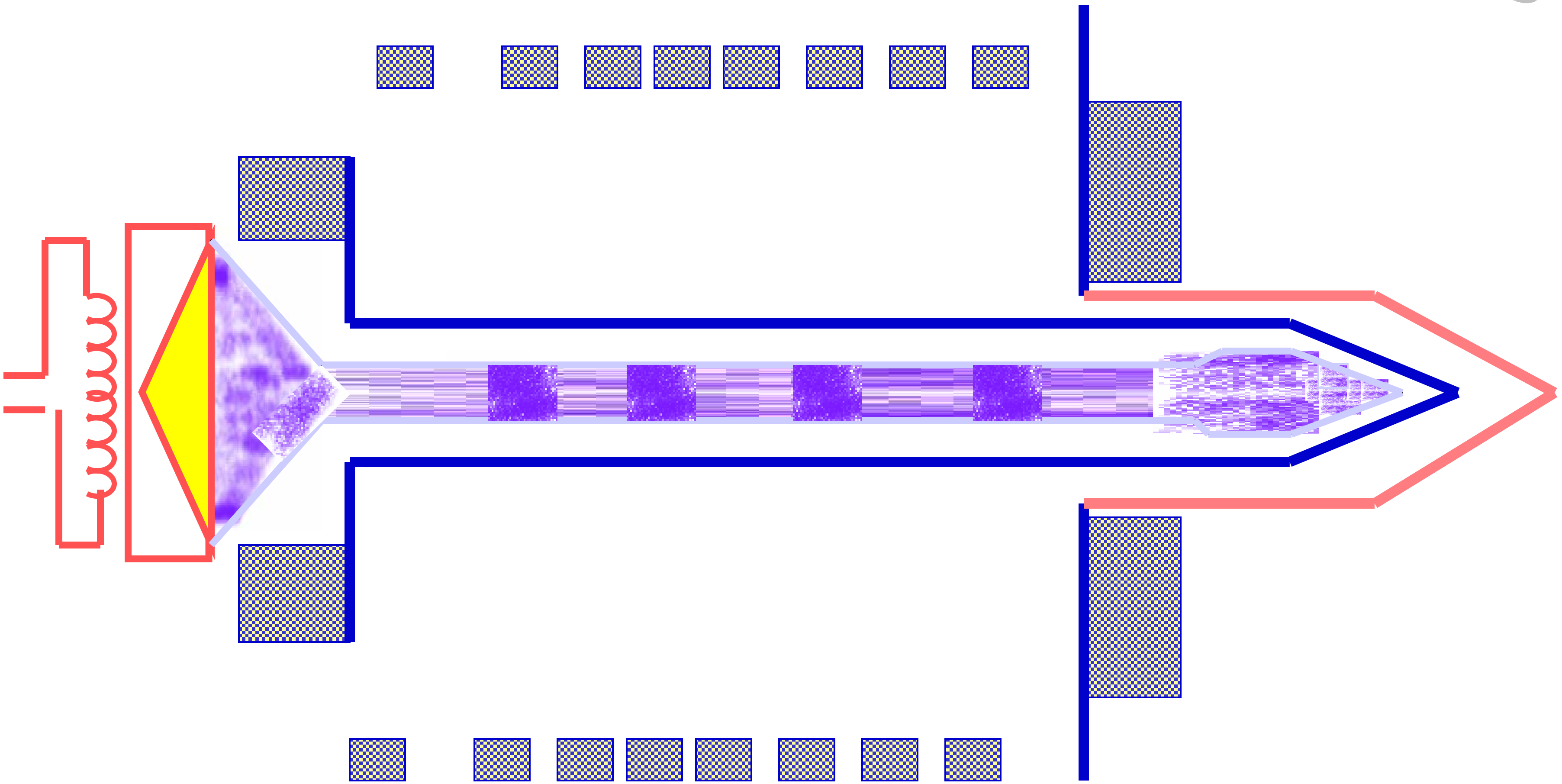
a) Inductive and capacitive components of the impedance are equal and opposite in sign and they cancel.

b) Internal circulating current is maximum, limited only by the resistive and dielectric losses of the cavity.

c) RF voltage across the gap is maximum.



Storage Ring



Klystron Beam Power

88 kV@12 A

Beam Power = 88kV × 12 A = 1056 kW

Klystron Operating Efficiency

$$\varepsilon(\%) = \frac{(Average\ RF\ Power)\times 100}{Average\ Beam\ \ Input\ Power} = \frac{500\,kW \times 100}{1056\,kW} = 47.3\%$$

Collector Water

Flow = 400 gpm **T_{in} = 30 °C** **T_{out} = 35.17 °C**

Power (kW)= (0.264)(ΔT °C)(Flow gpm)

Power (kW)= (0.264)(5.17 °C)(400 gpm)=546 kW

RF Output Power	+	Body Dissipation	+	Collector Dissipation	=	Beam Power
500 kW	+	10 kW	+	546 kW	=	1056 kW